Investigation of Hand Exoskeleton Design Characteristics on Precision Grip Performance

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https://hdl.handle.net/2324/7157352

出版情報：Kyushu University, 2023, 博士（工学）, 課程博士
バージョン：

Kyushu University
Graduate School of Design

Investigation of Hand Exoskeleton Design Characteristics on Precision Grip Performance

精密グリップ性能に及ぼす手外骨格設計特性の研究

Dissertation

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September, 2023

Supervised by,
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Abstract

A deficit in hand function will bring difficulties in daily activities. Meanwhile, a hand exoskeleton (HE) is a device that has the potential to assist hand function. However, the current HE design prioritizes muscle power assistance, while most of the hand activities are actually fine hand use carried out by precision grips in which hand joint mobility is important. Moreover, the strength-oriented design of the HE has the potential to reduce hand joint mobility. Therefore, this research aimed to study the human-machine interaction on an HE, which is focused on the interaction between mechanical design characteristics of the HE and the joint mobility function of the user's hand in fine hand use activities. For this purpose, a three-digit HE prototype was prepared to fit each participant's hand.

The first study of this thesis aimed to investigate the effects of the weight and DOF of the HE on the hand joint mobility function while performing fine hand use activities. A productivity task (performed with Standardized-Nine Hole Peg Test) and motion tasks, both performing the tip pinch and tripod pinch, were conducted to measure the task completion time and the range of motion (ROM) of the digit joints, respectively, using a motion capture system. This study concludes that wearing an HE will generally reduce hand joint mobility due to the movement resistance from its mechanical system. However, additional weight to the digits may improve the movement range aspect of hand joint mobility.

Because the digit's weight potentially counterbalances the mechanical resistance of an HE, the second study of this thesis aims to investigate the effects of the counterbalancing force of the HE on hand joint mobility function. The one-

direction counterbalancing force was actively exerted on the prototype. Investigation of DOF reduction during counterbalancing was also included. Measurement of the motion task using a motion capture system was conducted to measure ROM, angular velocity, and angular acceleration of hand joints. This study found that the counterbalancing force has the potential effect to work against the movement resistance. The counterbalancing force improved hand mobility on high-movement joints and its application on joints with low movement resistance was detrimental.

From the two studies, it can be concluded that DOF and the weight of the digits of an HE are important factors to consider in designing an assistive HE for daily use. While DOF reduction will reduce hand joint mobility, digits' weight addition in a certain condition might generate a counterbalance and improve movement range. Active counterbalancing has also shown its potential. However, a strategy to apply the counterbalancing force is required because it works differently for each joint. These results might bring implications to future HE designs, especially regarding the implementation of a certain linkage system and new control strategy of the HE.

Acknowledgments

I thank God (الرحمنا لرحيم) for the completion of this thesis. Only with His grace does the whole universe mysteriously work to make it happen. Therefore, apart from praising Him, I sincerely thank everyone who contributes directly and indirectly to this work.

In particular, I thank Prof. Satoshi Muraki for his extraordinary support in all stages of this thesis and for the research financing through JSPS KAKENHI (No. JP17H01454 & JP21H04898). I also thank Prof. Osamu Fukuda (Saga University) and Dr. Ping Yeap Loh for their brilliant inputs on this research.

I thank all members of Muraki's Laboratory and the Kyushu University Human Science Department, especially, and Dr. Wen Liang Yeoh for his idea and contribution to my scientific publication. Then, to Dr. Shin Takesue, Dr. Jeewon Choi, and Dr. Hiroki Nakashima who were involved in the preparation of my experiments, I really appreciate their contribution.

I thank Ms. Sachi Takahashi, secretary of Muraki's Laboratory, for procuring the tools and materials for my experiments. My deepest thank also goes to the administration office of Kyushu University Ohashi Campus for the support during our stay in Fukuoka and of course for the processing of this thesis.

I thank my wife and two children who are always patient in accompanying me and making everyday life enjoyable. Last but not least, I thank my parents for their continuous motivation and everyday prayers to make me become a better person.

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Priadythama, I.; Yeoh, W.L.; Loh, P.Y.; Muraki, S. (2022). The Effect of the Degree of Freedom and Weight of the Hand Exoskeleton on Joint Mobility Function. Robotics, 11, 53. https://doi.org/10.3390/robotics11020053

Chapter 1

General Introduction

1.1 Hand Function

Hands are instruments of the human upper limb that have unique characteristics. High sensitivity allows their movement to be delicate and accurate. However, they can also perform powerful and instantaneous actions (Schreuders, Brandsma, & Stam, 2019). The unique characteristics of the hands enable them to perform tasks that require a combination of intricate movements and finely controlled force. The biomechanical ability of the hands is supported by its complex anatomical system, where each part supports the other. The relationship among these parts is very crucial and a functional deficiency in any of these, even very small structures, can alter the overall function of the hands (Schreuders, Brandsma, & Stam, 2019).

Considering its multi-joint structure, two body functions primarily support the abilities of the hands. The first is the hand joint mobility function, which includes the range and ease of movement of the joints providing flexibility (WHO, 2001). Along with control and coordination, high flexibility enables the hand to perform careful and precise movements. The second function is hand-muscle power. This function is related to the force generated by the contraction of the muscle or muscle group of the hands (WHO, 2001). The power produced from the muscle contraction allows the hands to hold and manipulate a heavy object or generate fast movements. Hand dexterity, produced by both speed and precision, is supported by both joint mobility and muscle power.

A deficit in hand function can be caused by disease or trauma (Krupp, Peltner, & Zumhasch, 2019). Aging may also reduce hand functions. A study on the effects of aging on hand functions confirmed that handgrip strength and pinch steadiness decreased significantly with aging (Ranganathan, et al., 2001). A deficit in hand function will impact independence in performing activities, including activities of daily living (WHO, 2001). **Figure 1.1** shows that body function is a critical component directly associated with activities.

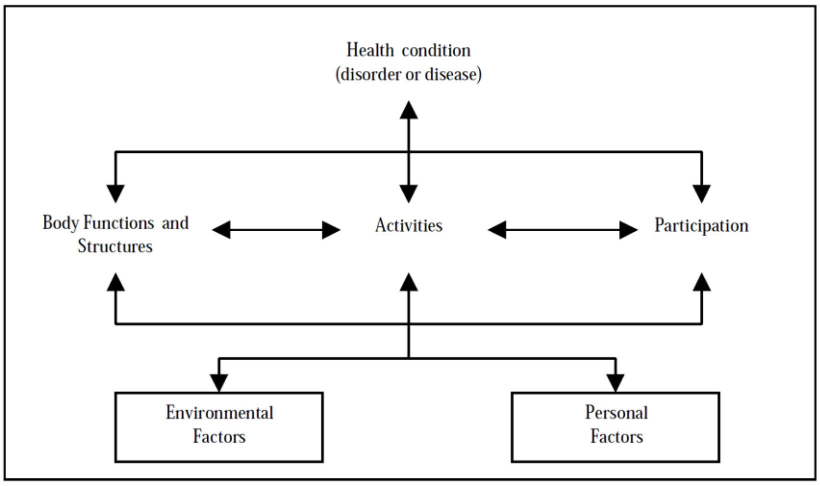


Figure 1.1 International Classification of Functioning, Disability, and Health (ICF) Model: the relationship between body functions, activities, and other related components. (WHO, 2001).

In the workplace, many activities require the use of hands. Some activities rely only on hands and arms. A hand function deficit in working activities is caused by low hand fitness and the gap between personal capacity and work requirements. The gap potentially occurs when a working task is categorized as high load, long duration, or high repetition and requires a highly fit hand condition or even exceeds the average normal human hand ability. In addition, it can reduce productivity in completing tasks and accelerate grip fatigue, which further reduces work performance (Mahdavi et al., 2020).

1.2 Hand Exoskeleton (HE)

A HE is a wearable device that covers the palm and digits (fingers and thumb) and can assist in hand function. Adapted from HE reviews and classifications (Mozaffari-Foumashi, Troncossi, & Castelli, 2011; Heo et al., 2012; Bos et al., 2016; Shahid et al., 2018; Ferguson, Shen, & Rosen, 2020; du Plessis, Djouani, & Oosthuizen, 2021; Noronha & Accoto, 2021; Tran et al., 2021), HEs can be classified based on its purpose, signal, energy, and mechanical features (**Figure 1.2**). The assistive HE was developed mainly for assisting with daily activities (Noronha & Accoto, 2021). Assistive HE is externally powered and has a structure similar to that of hand orthosis (Bos et al., 2016). The outer construction of the HE is broadly classified into three types: soft, rigid, and hybrid (combination) (Noronha & Accoto, 2021).

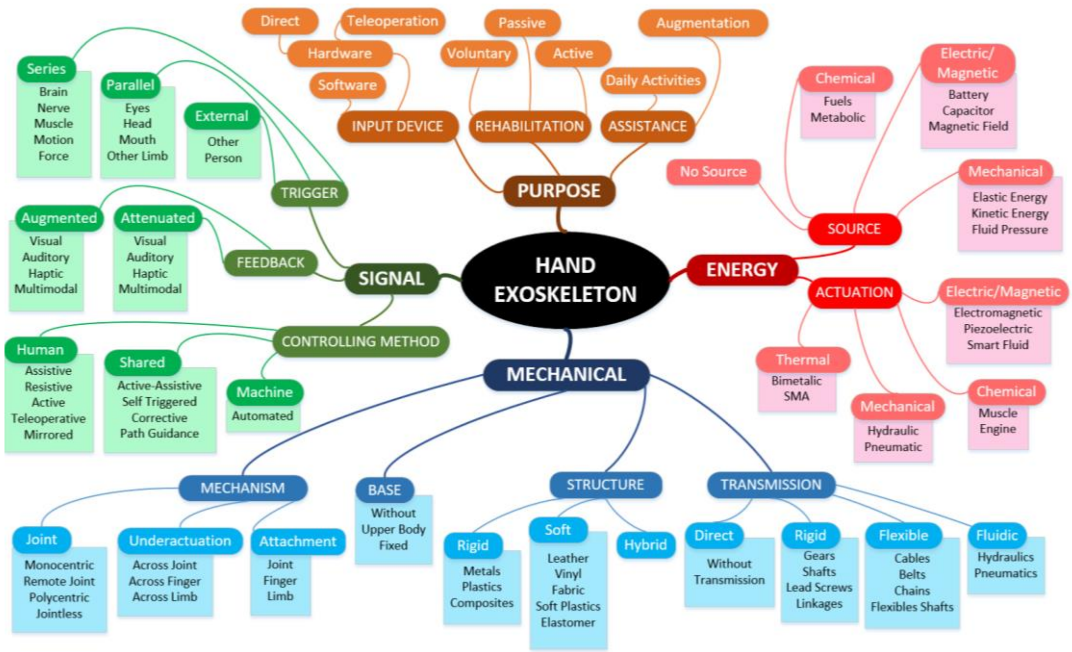


Figure 1.2 Hand Exoskeleton Classification

A soft HE has a flexible case or glove-like structure that does not limit the natural movement of the hand joints (Noronha & Accoto, 2021). Some are equipped with thick or stiff segmental parts that can support their structural stability when actuated. Meanwhile, the flexible parts maintain the integrity of the segmental parts. This design minimizes the effect of the geometrical mismatch between the device and the user's hand, thus allowing comfort in wearing. Some types have a flexible actuator system installed on the back of the palm, which limits the exerted force. Other models, equipped with a pulling cable transmission system, can provide a high grip force; however, because the mechanism is on the palmar side, it causes a reduction in gripping and tipping sensations, especially when the glove is used as the flexible case.

A rigid HE is composed of stiff materials (Noronha & Accoto, 2021), with mechanical parts on the palmar side. Mechanical joints are used to maintain the integrity of segmental parts. The linkage mechanism is commonly used as a power transmission system for digit segments. It is also used to reduce the number of actuators, namely under-actuation. It has excellent geometrical stability and movement precision but has a very high risk of the geometrical mismatch effect. This mismatch reduces comfort as well as hand performance. Moreover, wearing rigid HE is troublesome because of segmental parts positioning and fixation, which usually utilizes straps or adhesive tapes. Well-placed straps will keep the palmar side uncovered, thus ensuring uninterrupted gripping and tipping sensations. Rigid HE with a linkage system can provide a large and precisely distributed assistive force.

1.3 Design of Rigid HE

The majority of assistive HE designs adopt a rigid structure with a bar linkage mechanism for power transmission (Bos et al., 2016). This design has the advantage of creating a firm attachment (Lambelet et al., 2020) with a free palmar side, thus allowing the hand to interact directly with the environment (Mozaffari-Foumashi, Troncossi, & Castelli, 2011). A firm attachment is important for accurate force delivery (du Plessis, Djouani, & Oosthuizen, 2021). **Figure 1.3** shows the diagram of a typical rigid HE design. The actuators that are commonly fixed to the user's carpal produce a pushing force transmitted into the flexion of the digits by the linkage mechanism. The bar linkage mechanism design may vary from a single pushrod that pushes one of the three segments of the digit to the most complex, which pushes all segments at once. Typically, the pushrods are connected to a segment structure that covers half of the top of the digits.

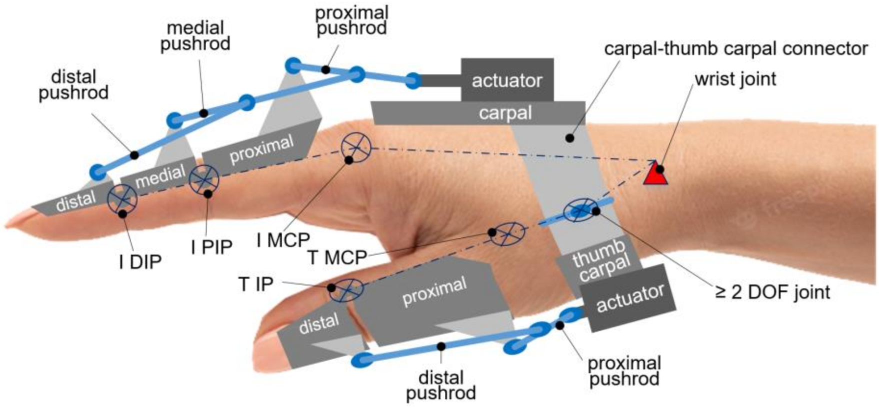


Figure 1.3 Typical design of rigid hand exoskeleton

The degree of freedom (DOF) is defined as the number of planes in which a joint can move (Hamill, Knutzen, & Derrick, 2015). The hand is composed of many joints with a total of 27 DOF (El Koura & Singh, 2003). To accommodate hand flexibility, rigid HE should adopt a multi-joint structure (Marconi et al., 2019; Sarac, Solazzi, & Frisoli, 2019). To enable the joints to move smoothly, the joint fitting should be produced with a gap but with minimum looseness (Erkaya, 2017; Shafiei & Behzadipour, 2020). At the proximal and distal interphalangeal joints, HE often uses concentric joints (a rotational joint placed on the joint of the digits) (Bos et al., 2016). At the metacarpophalangeal joints, a jointless structure, remote center mechanism, or parametrized model is generally used (In, 2011; Ferguson, Shen, & Rosen, 2020; Li et al., 2021). In contrast, for the thumb carpal, a joint with more than two DOF or a combination of joints is used (Cempini, 2015).

When two or three-digit segments are pushed together (which is commonly used in the under-actuation design), a linkage mechanism that produces interdependent motion is required (Wu, Carbone, & Ceccarelli, 2009). Once the linkage is attached, there is a reduction in the digit's DOF. To maintain the functionality of the hand, the length of the linkage mechanism, including the digit structures, should be optimized (Wu, Carbone, & Ceccarelli, 2009). Moreover, the attachment position of the digit structure to the user's digits must be correct. However, considering the narrow gap between digits, the lateral dimension of the linkage mechanism must be small or the side wall of the digits must be as thin as possible.

The major consideration in choosing a material for assistive technology (AT) is that it is strong but lightweight (Cook & Polgar, 2015), with no exception for the rigid HE. A rigid HE has several heavy parts, such as actuators or bolts; thus, the lightness of the structure is an advantage. As the digits are more dynamic than other parts during hand movements, the lightweight structure has a greater advantage (Hirt et al., 2017). Some types of plastics are known to be lightweight and strong, comparable to lightweight metals (Ashby, 2016). Plastics can also provide elastic deformation at a low force, which can improve wearing comfort that affects hand performance (du Plessis, Djouani, & Oosthuizen, 2021). Polylactic Acid is a plastic that is commonly used as the HE material, not only because it has sufficient strength but also because it is quite easy and cheap to customize by 3D printing (du Plessis, Djouani, & Oosthuizen, 2021).

Mechanical parts with multi-articulated joints produce movement resistance from friction, inertia, and misalignment. For HE, resistance causes difficulty in low-force and precision movements. This resistance can be reduced or neutralized by using a counterbalancing or compensation force. The counterbalancing force counters another force with the same magnitude but in the opposite direction (Popov, 1990). A previous study attempted to reduce resistance in cable transmission of a rehabilitation-purposed HE by controlling the compensation force (Wang, Li, & Zheng, 2014). Another study used the counterbalancing force concept in their anthropomorphic robot arm, which can potentially be adopted by other ATs (Whitney & Hodgins, 2014). However, the application of a counterbalancing force for assistive HE is still rare.

1.4 Current Issues in HE

Although HE was first introduced in the early 1990s (Shields et al., 1995), it is still difficult to find assistive-purposed HE in the market. Providing HE with daily assistance capabilities is the greatest challenge in HE development (Noronha & Accoto, 2021). Previous studies have demonstrated the potential of HE in alleviating grasping function (Triolo, Stella, & Busha, 2018; Lince et al., 2017). However, most HE development is still in the conceptual or experimental stages. Promising results have been obtained in the development of rehabilitative HE for people with hand disabilities (Kim et al., 2017). These results are promising because their target was to recover basic grip function, which is much simpler than fully functioning hand grip and posture variation in daily activities.

As a type of AT, assistive HE should enable user participation in daily activities (Cook & Polgar, 2015). Considering this, the HE development process should understand the user's hand activities, instead of directly determining hand function gaps or seeking technological opportunities to close the gaps. Previous studies have mostly focused on the technological approach, and examinations have only been conducted on a narrow range of activities (Bos et al., 2016). As a result, the current research progress is insufficient to bring assistive HE to a high technology readiness level (Noronha & Accoto, 2021). Indeed, the initial development process can be time-consuming and may require dedicated studies and experiments; however, it can result in important findings that can lead to an accurate design.

Previous research on hand activities revealed that more than 50% of hand activities are fine hand use activities that require precision grips, which were mostly pinches, whereas power grips only accounted for 31% of activities (Vergara et al., 2014). Precision grips require functions that support hand flexibility, and mobility of the hand joints (ease of movement and movement range) is required in addition to the muscle's producing force. However, most of the current HE designs are focused on improving grip strength, often at the expense of reducing the flexibility of the user's hand, which eventually lowers its performance in precision grip. Conversely, HE designs that maintain hand flexibility generally provide only a limited assistive force.

HE is a complex device; thus, improving only its method of control will still make it difficult to generate a wide range of functions for the HE (Soekadar et al., 2015). However, optimizing the mechanical design of the HE is a possible approach to improve performance (Bianchi, 2020). As explained in detail in the second chapter, the mechanical design characteristics of the HE, including the DOF of the digits and the weight of the digits, could potentially influence the hand joint mobility function and eventually affect its performance in fine hand use activities. While the reduction in the DOF tends to decrease hand mobility with a decrease in hand flexibility, the addition of weight has a similar tendency due to inertial resistance. However, both still have the possibility of improving movement control because of their support in muscle tone.

Regardless of its potential benefit, the counterbalancing force feature is rarely adopted in HE, and its effect on the user has not yet been studied. Passive counterbalance has been widely applied in industrial robotics, including robotic arms (Whitney & Hodgins, 2014). However, the dynamic hand characteristic during its activities makes a passive counterbalance ineffective in every situation. However, providing an active counterbalancing force for HE remains unresolved (Wang, Li, & Zheng, 2014). The existence of an additional control system to provide the counterbalancing force is limited by the low-complexity key feature of HE; thus, a simple control strategy should be adopted. How the user interacts with this system has become an interesting new area of study.

1.5 Aims, Scopes, and Outline of The Research

While most research related to HE is in the field of engineering, this doctoral thesis investigated the human approach to HE usage. **This research aimed to study the human–machine interaction on an HE, which is focused on the interaction between mechanical design characteristics of the HE and the joint mobility function of the user's hand in fine hand use activities.** This research specifically observed the tip pinch and tripod pinch, the two most frequently used precision grips in fine hand use activities. The prototype used in this study was the rigid HE, which is the most adopted assistive non-rehabilitative HE design. The mechanical characteristics of the HE that were investigated were the DOF and the weight of the digits. Two studies were conducted to achieve this objective.

Chapter 2 of the thesis is entitled "**Effects of the Degree of Freedom and the Weight of the Hand Exoskeleton on Joint Mobility Function"**. This is the first study in this thesis that aims to investigate the effect of DOF and weight of the HE on hand joint mobility. In this study, a passive prototype was developed for each participant and two separate measurements were conducted for ease of movement and movement range. In the first measurement, a dexterity test was performed using a standardized nine-hole peg test to measure hand productivity, which represents the ease of movement under various DOF and weight conditions. In the second measurement, a motion analysis was performed using a customized peg test to analyze the change in the digit's joint movement range after wearing the various HE setups. The results of this study can be used to answer questions about user interactions that occur in current rigid HE designs. The findings of this study provide insights into the solution and design direction for highly effective HE for daily use.

Chapter 3 of the thesis is entitled "**Effects of the Counterbalancing Force of the Hand Exoskeleton on Joint Mobility Function"**. This is the second study that aims to investigate the effect of the counterbalancing force of the HE on joint mobility. This study is a continuation of the findings of the first study, which indicates the counterbalancing role of finger loads against motion barriers that eventually result in an improvement in the range of movement. To provide a counterbalancing force, an externally powered HE was prepared for each participant. Motion analysis was performed using a customized peg test. The movement ranges of each counterbalancing force setup were compared. The results of this study demonstrate the potential application of a counterbalancing strategy in a rigid HE. This study provides findings regarding user interaction with a counterbalancing strategy, which is essential for assistance-purposed HE development.

Chapter 4 is entitled "**General Discussions"**. This chapter summarizes the results and findings of the first and second studies to address the general issues related to the mechanical design of a rigid HE. Findings related to design are also compiled and discussed to provide a highly comprehensive design direction for HE development. The limitations and future scope of each study are also listed and reviewed, along with the general conclusion of this thesis.

Chapter 2

Effects of the Degree of Freedom and Weight of the Hand Exoskeleton on Joint Mobility Function

2.1 Introduction

The hand exoskeleton (HE) is a promising assistive technology (AT) solution for improving hand function (Ferguson, Shen, & Rosen, 2020). However, providing an effective HE for assisting with daily activities remains the greatest challenge (Noronha & Accoto, 2021). HE designs should be capable of assisting main daily hand activities, fine hand use activities, and rough activities (Vergara et al., 2014). However, most HE designs that are capable of delivering sufficient force have characteristics that reduce hand joint mobility which is very important for performing fine hand use activities (WHO, 2001). Providing both sides' capabilities through HE's control system remains difficult (Soekadar et al., 2015), and it is important to explore strategies for managing this problem. Managing the mechanical system of HE is a possible approach to performing HE (Bianchi, 2020).

Reducing the degree of freedom (DOF) by adopting an intra-finger under-actuation concept is the most common strategy to reduce the complexity of an HE (Bos et al., 2016). A linkage system that transmits power from a single actuator to multiple finger segments is typically used. However, this concept has several limitations. The more mechanical joints are applied, the more the friction source is present (Popov, 2017). Even though joint friction can be maintained at a low level by setting the clearance and applying lubrication (Ludema & Ajayi, 2018), the digit segments are interdependent; thus, some movements are restricted. Movement restrictions can lead to a reduction in hand mobility function (Bensel, 1993; Rondinelli et al., 1997; Wells, 2010). However, movement restriction may also be beneficial because undesired motion may be suppressed, which may improve precision (Fromme et al., 2020).

A higher hand weight can decrease the ability to perform fine hand use activities (Bensel, 1993). In general, the more powerful the HE, the heavier it is. A high assistive force is commonly produced by a large actuator. To withstand high forces, a thicker structure or stronger material is required (Popov, 1990). All these components increase the weight of the HE. As an illustration, a 1.2 kg HE can provide a 30 N grip force (Troncossi, Mozaffari-Foumashi, Castelli, 2016) while a 100 g system, only produces less than 2 N (Nycz, 2016). Even though the addition of weight may seem detrimental, counterintuitively, heavier weight may improve movement control. A case example shows that adding weight to the hand of people with impaired muscle tone can effectively suppress vibrations, thereby increasing the precision of their hand movements (Faizan & Muzammil, 2020; Masoumi et al., 2021).

From the description above, the DOF and weight are the two mechanical design characteristics of an HE that have potentially positive and negative effects. There remains a gap in the understanding of how these two factors affect the user's hand, especially in fine hand use activities. Therefore, this study aimed to investigate the effect of the weight and DOF of the HE on the hand joint mobility function while performing fine hand use activities. This investigation requires the design and realization of an HE prototype capable of DOF and weight changes. Several participants would use this prototype to perform productivity and motion tasks that measure the task completion time and the digits' motion range, respectively. In addition, the perceived ease of performing the tasks would be rated. The results would represent the hand joint mobility (the ease of movement and the movement range) which later would be analyzed and discussed. Based on the findings we would obtain, a solution to the motion barriers in wearing the HE would be proposed.

2.2 Materials and Methods

In order to achieve the objectives of this study, and in particular, to obtain the three parameters, an experiment involving several participants was conducted. A series of steps was needed to prepare and execute the experiment, as well as analyze the results. Illustrations of these steps are systematically presented in **Figure 2.1**.

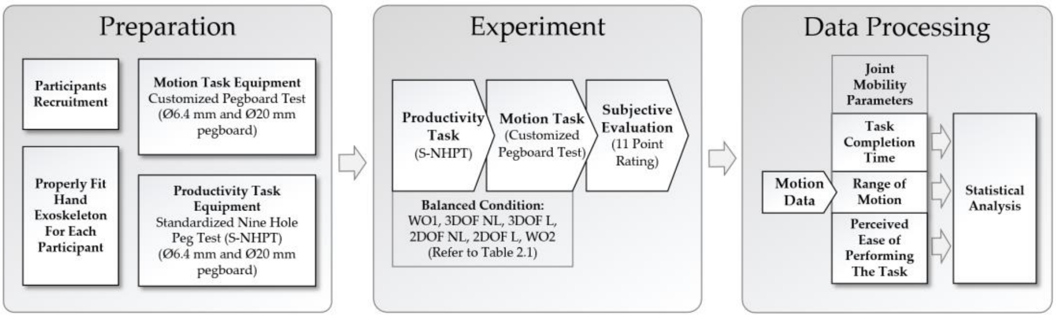


Figure 2.1 Flowchart of the experimental steps from the preparation to statistical analysis of the experiment data.

2.2.1 Participants

Twelve males, with a mean age of 26.8 ± 3.8 years, were recruited as experiment participants. All participants were right-hand dominant, tested by The Edinburgh Handedness Inventory (Oldfield, 1971). The non-dominant hand (187.0 ± 16.3 mm hand length) was confirmed to be free of health issues and fatigue from recent strenuous hand activity. All participants provided written informed consent for the experiment, and the experiment has been approved by the Research Ethics Committee of the Faculty of Design, Kyushu University (approval number 329).

2.2.2 Prototypes

Literature reviews have been conducted on prototypes developed in academia (Mozaffari-Foumashi, Troncossi, & Castelli, 2011; Heo et al., 2012; Bos et al., 2016; Shahid et al., 2018; Ferguson, Shen, & Rosen, 2020) and those developed by companies, such as Exo Hand (Festo SE & Co. KG, Esslingen, Germany). Although rehabilitative HE shifts to a soft structure (Shahid et al., 2018), most assistance-purposed HEs still adopt a rigid structure, a single-centered joint (to connect segments), and a bar linkage mechanism for transmission (Bos et al., 2016). This rigid structure is capable of firm attachment (Lambelet et al., 2020) so that the assistive force can be delivered precisely (du Plessis, Djouani, & Oosthuizen, 2021). This study used rigid HE prototypes as the experimental prototype, where the bar linkage mechanism was adapted from the Exo Hand (Festo SE & Co. KG, Esslingen, Germany). The 3-dimensional design of the prototype was built using Autodesk Fusion 360 (Autodesk Inc., San Rafael, CA, USA), as presented in **Figure 2.2.a**.

The HE prototype has 26 to 28 DOFs and is equipped with three exoskeleton digits (thumb-index finger-middle finger), which is sufficient for testing the effects of using a HE on several types of precision grips. The fingertip areas were designed to be free of any HE attachments and straps to maintain fingertip sensation during pinching. To achieve this, the double-sided tape was used to attach the prototype to the participant's hand. The structure of the digits was made to be thin to minimize the contact between the index and middle finger during the tripod pinch and the distal segments were not fully covered (only 75% of distal length) by the exoskeleton to avoid contact with the ground while performing the picking up motion.

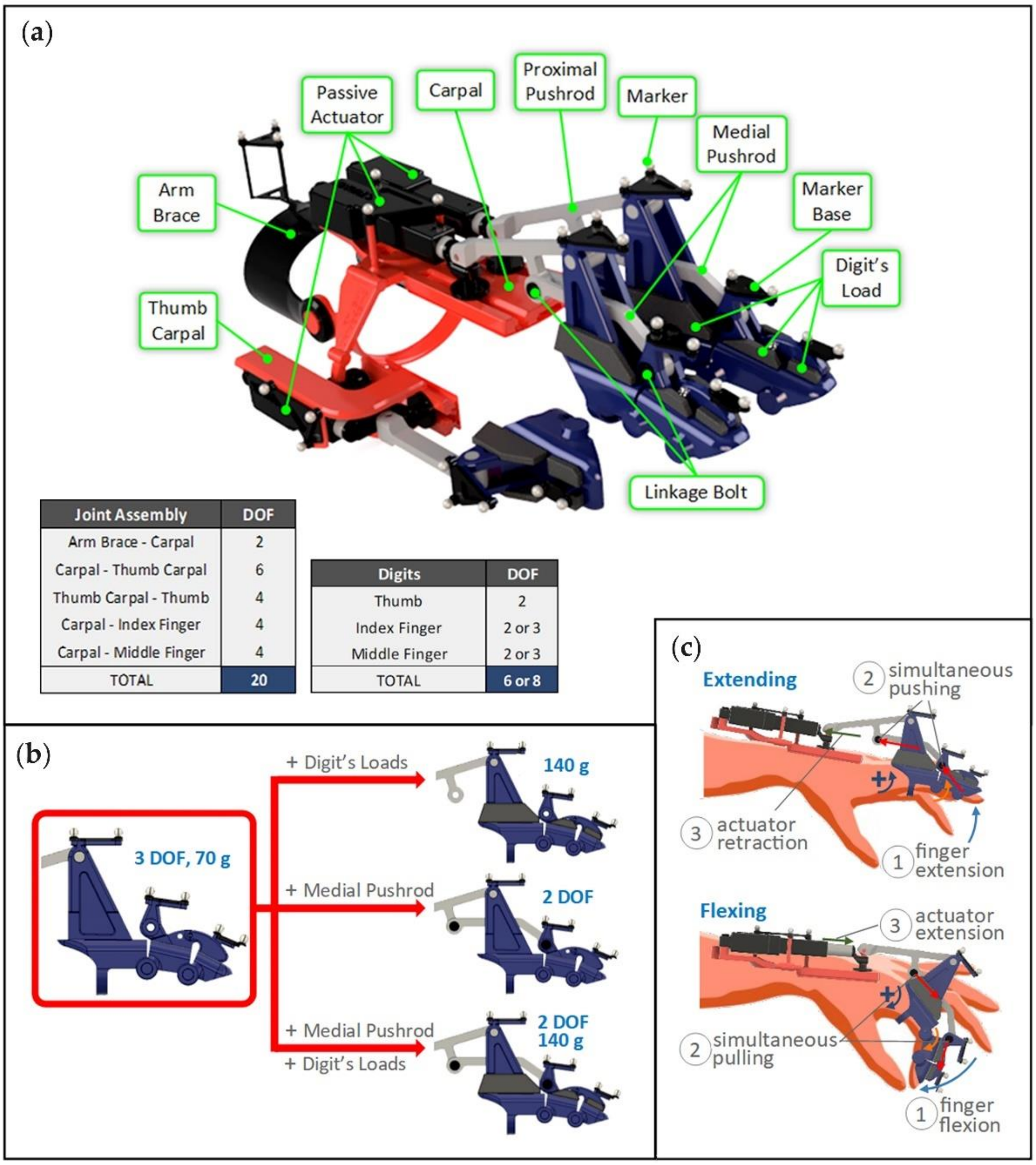


Figure 2.2 Hand exoskeleton prototype: **(a)** 3D assembly view and component's degree of freedom (DOF); **(b)** setting up digit's DOF and weight; **(c)** flexing and extending finger in 2 DOF setups.

The prototype allowed for the change in DOF by installing or uninstalling two medial pushrods on the HE (**Figure 2.2.b**). A medial pushrod connects the proximal pushrod to the medial segment of the exoskeleton finger. As a result, when the finger is flexing or extending, the proximal and medial segments would move simultaneously, constraining the exoskeleton finger to only two DOF. Conversely, when the connection is removed, the exoskeleton finger becomes three DOF. This DOF-changing mechanism (interdependent proximal and medial segments) was selected to avoid bulky structures near the distal segment, which can disrupt pinching. To support the motion of this linkage mechanism, a passive linear actuator with a soft spring inside (0.1 N/mm rate) was installed to provide force at the beginning of digit flexion against friction to avoid jamming. The actuator's force at the pinch position is very small and can be neglected. **Figure 2.2.c** shows how this linkage system works.

Loads (**Figure 2.2.a** and **Figure 2.2.b**) were attached to each segment of the exoskeleton digits to allow for weight change. The loads were made from cut tin plates and had a total weight of 70 g. The loads were made to proportionally increase the weight of the exoskeleton digits. Attaching the loads doubled the weight of the HE digits, from 70 ± 5 g to 140 ± 5 g. As shown in **Figure 2.2.b**, the loads were carefully designed and placed to not increase the size of the HE digits, to allow for attachment and detachment, and not interfere with the linkage mechanism.

The prototype was designed for the participant's left hand (non-dominant hand) because the dominant hand (right hand) has higher functional abilities Cary & Dipcot, 2003; Ozcan et al., 2004; Noguchi, Demura, & Aoki, 2009) which could potentially hamper the effect of the studied factors. The size of each HE prototype was customized according to the anthropometric measurements of each participant's hand. Therefore, each participant received an HE prototype that fit properly. Additionally, all prototypes had similar motion characteristics when the two DOF modes were set by heuristic optimizations that were conducted using SAM 7.0 (Artas-Engineering, Netherlands), a mechanism design software (**Figure 2.3.a**). The finger motion characteristics were optimized to maintain the same metacarpophalangeal (MCP) joint to proximal interphalangeal (PIP) joint angle relationship among all prototypes. This relationship (**Figure 2.3.b**) was adapted from a model of natural finger movement (Jo et al., 2019).

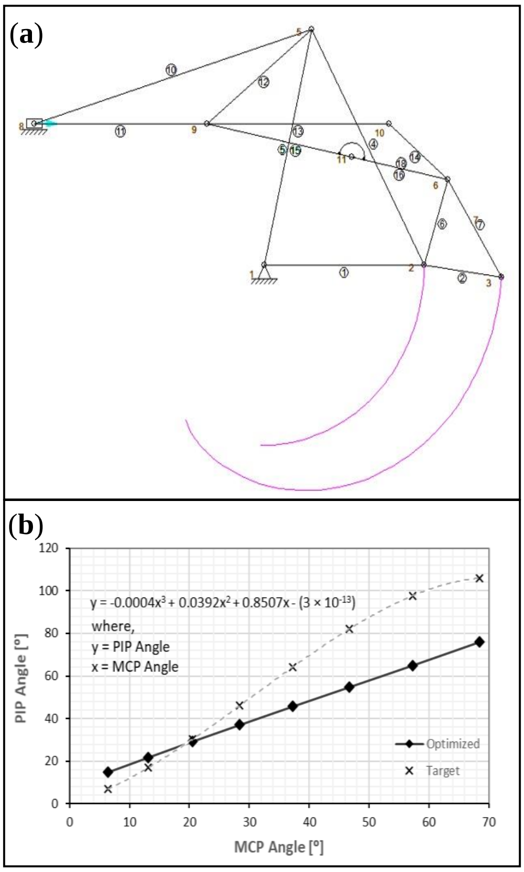


Figure 2.3 Two DOF linkage mechanisms **(a)** linkage mechanism design in SAM 7.0; **(b)** MCP to PIP joint relationship in optimized linkage versus target (natural finger movement)

For motion capture purposes, 28 retro-reflective markers with Ø4 mm (Nikon, Japan) were attached to the prototypes. Two or three markers for each segment were mounted on a base (a black small plate) before being attached to the prototype segments for fast installation on both the HE prototype and the barehand of the participants. The bases were made thin and light; thus, the weight addition towards the HE or hand can be neglected. When the HE is worn, the base for the markers on the proximal and medial segment (on the proximal segment for the thumb) and mounted on the top of the outer part of the linkage hinge, which is integrated with the structure of the digits (**Figure 2.2.a**). This placement makes the markers move together with the digits segment without interfering with the work of the linkage mechanism. The arrangement and list of markers on the prototype are shown in **Figure 2.4.a** and those on the barehand in **Figure 2.4.b**.

(**a**) (**b**)

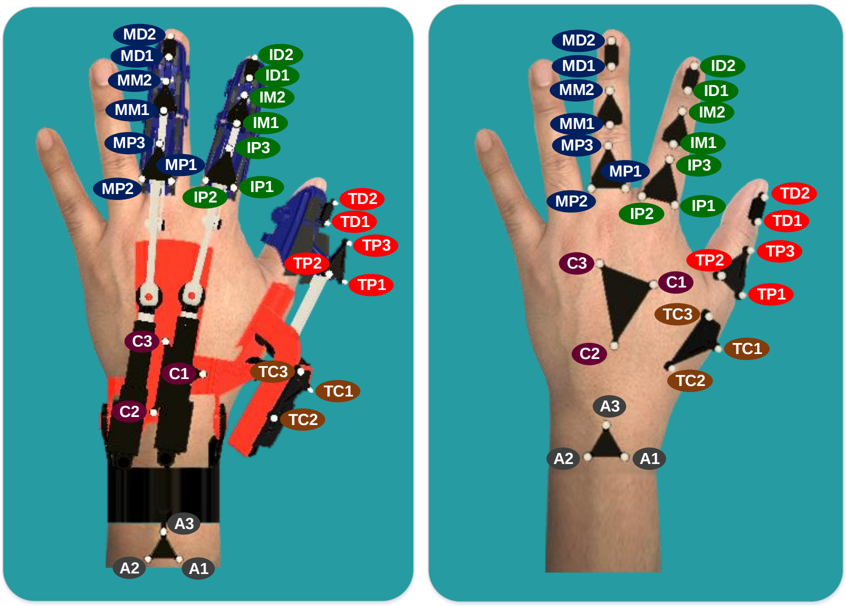


Figure 2.4 List of markers: **(a)** on hand exoskeleton; **(b)** on barehand.

2.2.3 Experiment Task

Two types of tasks were used in this experiment, the motion task and the productivity task. The motion task is designed to measure the range of motion (ROM) of the hand joints by analyzing the markers' position on the carpal and digits using motion analysis. Meanwhile, the productivity task is prepared to measure hand productivity through task completion time.

Pegboards for customized peg tests were prepared for the motion tasks, while a standardized nine-hole peg test (S-NHPT), as used by Johansson & Häger (2019), was selected for the productivity task. The pegboards for both tasks were prepared in two sizes, namely Ø6.4 mm peg for two-finger pinch (tip pinch) and Ø20 mm peg for three-finger pinch (tripod pinch). The criteria for choosing the Ø6.4 mm peg was based on the original nine-hole peg test introduced by Mathiowetz et al. (1985), while that for the Ø20 mm peg was based on the proper size pinching object for the tripod pinch (Feix et al., 2016).

The customized pegboard was 500 mm long with 10 holes (**Figure 2.5.a** and **Figure 2.5.b**). This board was designed only for a single peg to be manipulated. The peg had a flange to limit the position of the fingertip when pinching (**Figure 2.5.c**). A hole was designated as the initial peg position while the nine others were the target holes. The target holes were made with three different depths, 6 mm, 12 mm, and 18 mm for target holes no. 1 to 3, no. 4 to 6, and no. 7 to 9, respectively, to stimulate the articulation of the joints of the digits. The maximum hole depths were 1 mm shallower than those of the holes on the S-NHPT to ensure that insertion could be properly performed. To prevent fatigue while reducing arm movement, an arm slider was prepared to support the participant's forearm (**Figure 2.5.d**).

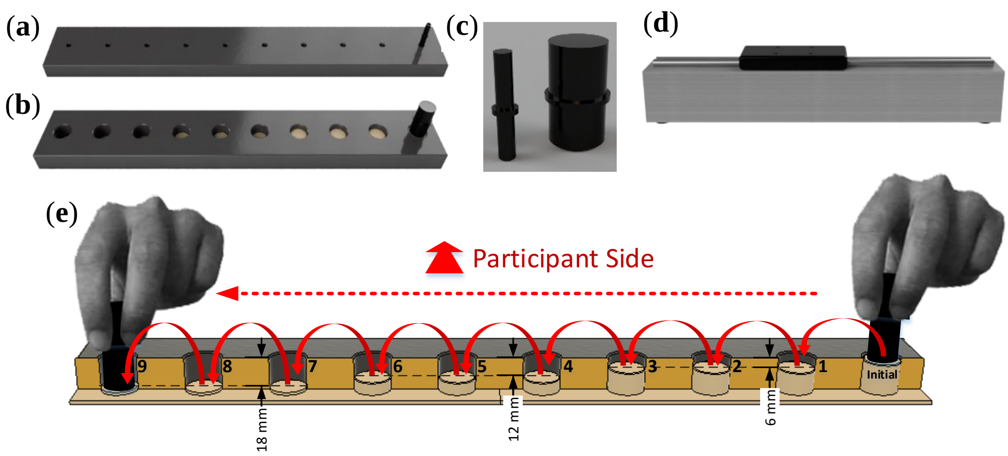


Figure 2.5 Customized pegboard test: **(a)** Ø6.4 mm pegboard for tip pinch; **(b)** Ø20mm pegboard for tripod pinch; **(c)** Ø6.4 mm and Ø20 mm peg; **(d)** the arm slider; **(e)** how to use the equipment.

The S-NHPT pegboard (**Figure 2.6.a** and **Figure 2.6.b**), consisted of two identical nine-hole peg test boards that were placed on a single wooden plate with a center-to-center distance of 18 cm. Each board was 127 × 127 mm in size. This test was designed for moving 9 pegs from one board (origin) to another board (target) in a predefined order. **Figure 2.6.c** shows that the shape of the peg is cylindrical without a flange, which indicates that no specific fingertip position is required during pinching.

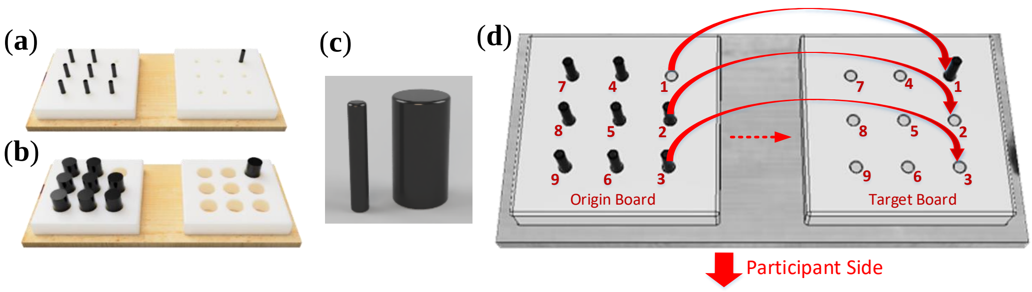
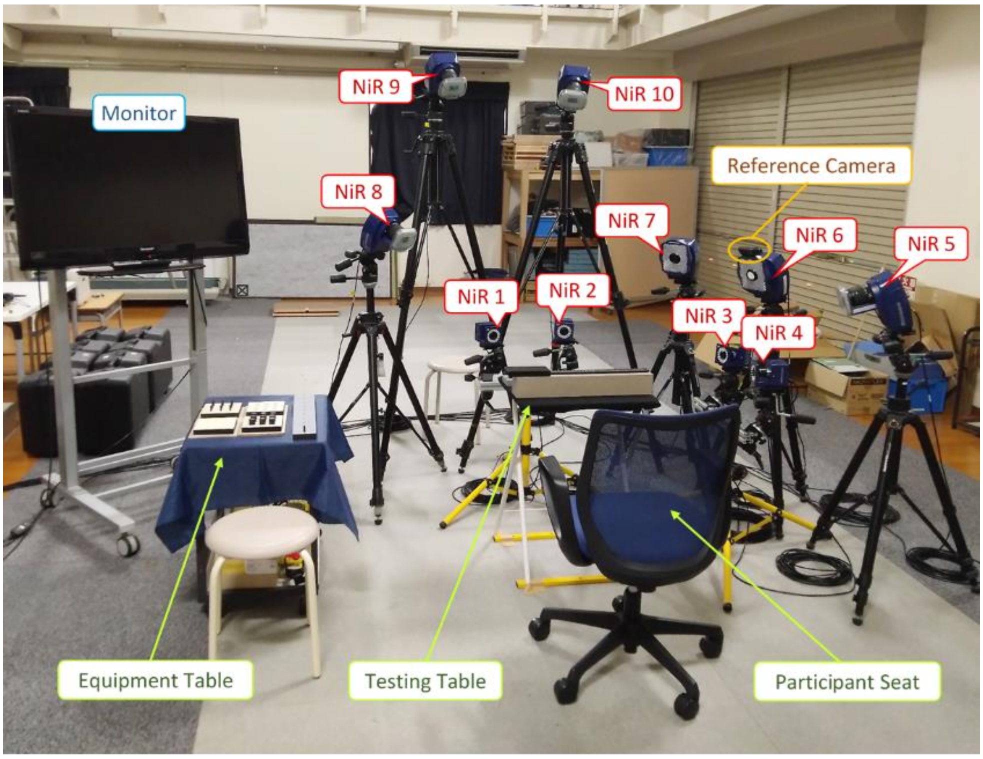


Figure 2.6 The S-NHPT: **(a)** Ø6.4 mm pegboard; **(b)** Ø20mm pegboard; **(c)** Ø6.4 mm and Ø20 mm peg; **(d)** how to use the equipment.

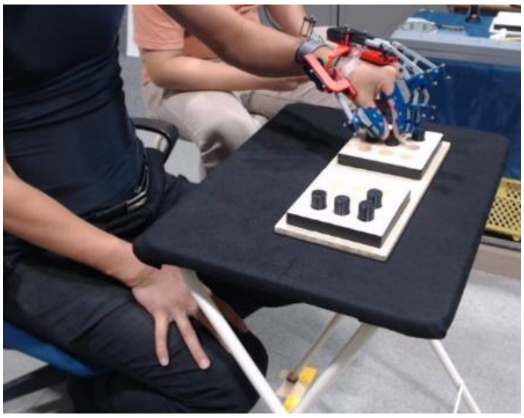
2.2.4 Setup and Procedure

The experiment was conducted in a dedicated space. The participant was made to sit on a chair in a comfortable upright posture while performing the task. The pegboard (both for the customized and S-NHPT pegboards) was arranged according to the reach of the participant's left hand. For the customized pegboard, the optimum position was achieved when the middle of the participant's body was in line with the position of target hole no. 7. Meanwhile, for the S-NHPT pegboard, the optimum position was in the middle of the target board. The pegboard was placed on a 60 × 40 cm testing table while near infra-red (NiR) cameras (Motion Analysis, Rohnert Park, CA) were arranged around the table. This participant position allowed an unencumbered view of the target hole, i.e., the exoskeleton did not impair visibility. The arrangement of the experimental apparatus and equipment is presented in **Figure 2.7.a**, while the participant positions are illustrated in **Figure 2.7.b** and **Figure 2.7.c**.

(**a**)



(**b**) (**c**)



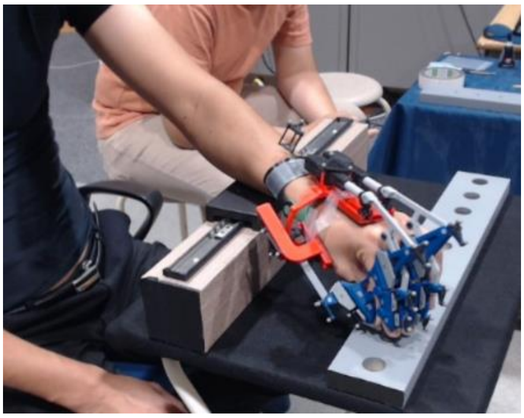


Figure 2.7 Experiment Environment: **(a)** apparatus and equipment arrangement, **(b)** participant position in productivity task, **(c)** participant position in motion task.

Six conditions based on the HE setup (**Table 2.1**) and two conditions based on the type of pinch (the tip pinch and the tripod pinch) were used in this experiment. The execution order of the setup conditions always started and ended without the participant wearing the HE so that the wearing and taking off the HE was only done once. The four conditions for wearing the HE (3DOF NL, 3DOF L, 2DOF NL, and 2 DOF L) were balanced using the Latin Square, whereas the pinch type conditions are balanced by reversing the execution order for half of the participants.

Table 2.1. Conditions based on hand exoskeleton setup.

Condition		**Annotation**
WO1		Condition without wearing HE (barehand) for the first run
balanced	3DOF NL	Condition with wearing HE with uninstalled medial pushrod (3 DOFs linkage) and no digits' loads attached (70 g digits weight)
	3DOF L	Condition with wearing HE with uninstalled medial pushrod (3 DOFs linkage) and all digits' loads attached (140 g digits weight)
	2DOF NL	Condition with wearing HE with installed medial pushrod (2 DOFs linkage) and no digits' loads attached (70 g digits weight)
	2DOF L	Condition with wearing HE with installed medial pushrod (2 DOFs linkage) and all digits' loads attached (140 g digits weight)
WO2		Condition without wearing HE (barehand) for the second run

The experiment was conducted in a systematic protocol with preparation, HE set-up, pegboard set-up, practice (with instruction), the task for both pinch types, and rest. Each task was executed thrice, and the average result was calculated before the statistical analysis stage. While resting after sequentially completing the productivity and motion tasks with the same HE setup, the participants were asked to rate the perceived ease of the condition that they had just experienced (for both the tip and tripod pinches).

For the customized pegboard test, the participants were asked to insert the peg until it touched the bottom of the holes, consecutively from hole no. 1 to 9 without adjusting the grip or releasing the peg (**Figure 2.5.e**). The participants were also instructed to perform the insertion motion as naturally and smoothly as possible. Conversely, in the productivity task, the participants were asked to move peg no. 1 to peg no. 9, one by one, from the origin board to the target board's corresponding holes as fast as possible. The procedure for this task is presented in Figure 6d. Because the tested hand was the left hand, the peg displacement direction was set to be opposite to the original version of the S-NHPT introduced by Johansson and Häger (2019).

2.2.5 Measurements

a. Task Completion Time

A motion capture system (Motion Analysis, Rohnert Park, CA, USA) was utilized to measure the task completion times. The measurement was based on the motions of the IM2 and MM2 markers, especially along the z-axis. Recordings by the reference camera were utilized to verify these motions. The task completion time was calculated by subtracting the end time from the start time of a task.

b. Perceived Ease of Performing the Task

Right after the participants had a chance to experience what it was like to perform the tasks with the HE setup for both the pinch conditions (tip pinch and tripod pinch), they were asked to fill out a questionnaire about the perceived ease of performing a task. The questionnaire was rated on an 11-point scale, from 0 ("extremely hard to do") to 10 ("absolutely easy to do"), with 5 as the neutral point (neither hard nor easy). At each filling, the participant was asked to rate the perceived ease for each of the pinch types (the tip pinch and tripod pinch).

c. Digit Joints' Range of Motion (ROM)

For measuring the digit joints' ROM, a motion capture system (Motion Analysis, Rohnert Park, CA, USA) was used. The recording rate was set to 100 Hz. The recorded marker position data were processed with the Cortex 7 software (Motion Analysis, Rohnert Park, CA, USA) to obtain continuous and clean motion data. Several virtual markers were added to allow ROM to be measured in planar motion. The names and locations of the virtual markers on the HE are presented in **Figure 2.8.a** and those on the bare hand in **Figure 2.8.b**. The exact positions of the virtual markers, used to produce or approximate planar motion, may differ across participants.

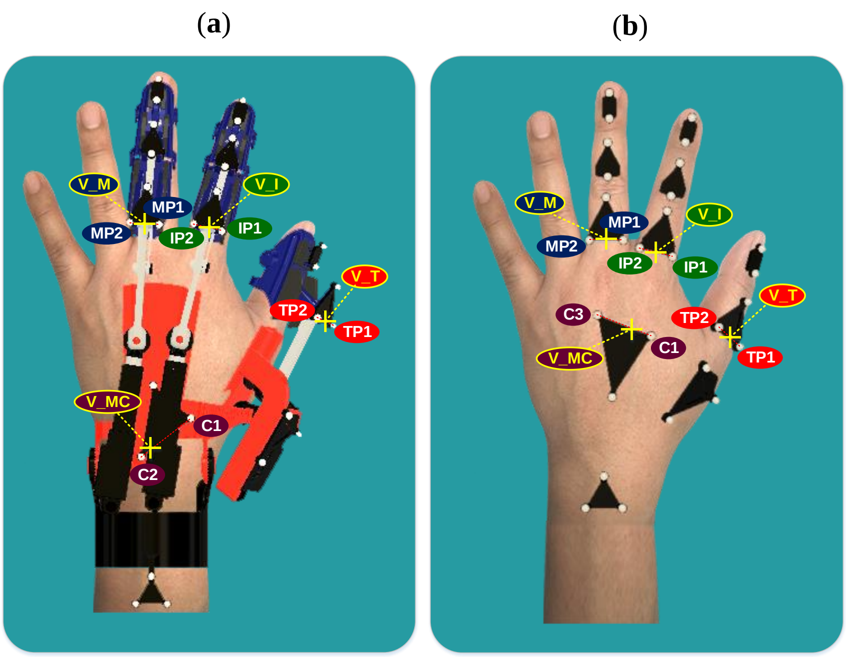


Figure 2.8 List of virtual markers: **(a)** on hand exoskeleton; **(b)** on barehand.

The data of the digit joint angles for measuring the ROM were processed using the four-marker angles method. In this method, an angle is defined by two lines that are each constructed by two markers. **Table 2.2** below lists the digit joint angles and their forming markers.

Table 2.2. List of digit joints and forming markers.

Digit	Digit Joint	Four Marker Angles [Line 1, Line 2]
Thumb	T MCP (Thumb Metacarpophalangeal)	From V_T to TP3, From TC3 to TC2
	T IP (Thumb Interphalangeal)	From TD1 to TD2, From TP3 to V_T
Index Finger	I MCP (Index Metacarpophalangeal)	From V_I to IP3, From V_MC to C2 (WO conditions)
		From V_I to IP3, From C3 to C2 (HE conditions)
	I PIP (Index Proximal Interphalangeal)	From IM1 to IM2, From IP3 to V_I
	I DIP (Index Distal Interphalangeal)	From ID1 to ID2, From IM2 to IM1
Middle Finger	M MCP (Middle Metacarpophalangeal)	From V_M to MP3, From C3 to C2 (WO conditions)
		From V_M to MP3, From C3 to V_MC (HE conditions)
	M PIP (Middle Proximal Interphalangeal)	From MM1 to MM2, From MP3 to V_M
	M DIP (Middle Distal Interphalangeal)	From MD1 to MD2, From MM2 to MM1

The ROM was defined as the difference between the maximum digit joint angle and the minimum digit joint angle, which resulted from the activity of inserting a peg into a hole up to a certain depth: 6 mm, 12 mm, or 18 mm. As there are three consecutive holes with the same depth, the joint angle is measured from the moment the peg reaches the bottom of the first hole until the peg reaches the bottom of the third hole.

2.2.6 Statistical Analysis

Prior to statistical analysis, the data of the two conditions without wearing the HE (WO1 and WO2) were averaged into a single WO condition as the baseline. For the productivity task, the baselines were used as a comparison against the conditions using the HE for the analysis of the task completion times and the perceived ease of performing the tasks, while in the motion analysis, the baselines were used to convert the ROM into ROM reduction to better show the impact of the DOF and weight factors on the ROM values. All data were checked for outliers (with Grubbs` Test) and missing values. All statistical analyses were conducted using the SPSS 24 software (IBM Corporation, New York, USA).

The measured task completion time and perceived ease of performing the task (as the dependent variable) were analyzed using the same statistical tools. Dunnett's test, at a significance level of 0.05, was utilized to analyze the difference between the conditions without wearing the HE (WO) and while wearing the HE (3DOF NL, 3DOF L, 2DOF NL, 2DOF L). Meanwhile, a two-way repeated-measures analysis of variance (ANOVA), at significance levels of 0.05 and 0.01, was applied to examine the effect of the factors (DOF and weight) on the dependent variables. To further explore the significant main effect with the significant interaction, a Bonferroni corrected pairwise comparison post-test was used. All these analyses were conducted separately according to the pinch types.

Similar to the tools used for the previous two parameters, two-way repeated-measures ANOVA was used to analyze the effect of the factors (DOF and weight) on ROM reduction, but in this case, at the 0.1 and 0.05 significance levels. A Bonferroni corrected pairwise comparison post-test was also used to further explore the significant main effect with a significant interaction. The analysis was separated based on pinch type (tip pinch, tripod pinch), depth of peg insertion (6 mm, 12 mm, 18 mm), and digit joint (T MCP, T IP, I MCP, I PIP, I DIP, M MCP, M PIP, M DIP). There were 39 separate analyses by the ANOVA.

2.3 Result

2.3.1 Task Completion Time

Based on Dunnett's test, wearing the HE showed a consistent drop in productivity with the task completion times being significantly higher in all conditions while wearing the HE compared to that at baseline. Meanwhile, ANOVA showed that DOF reduction ($F(1, 11) = [7.15]$, $p = 0.022$) and weight addition ($F(1, 11) = [12.98]$, $p = 0.004$) significantly affected the task completion time for tip pinch without any indication of interaction (**Figure 2.9**). A similar result was observed in the tripod pinch for the DOF effect ($F(1, 11) = [5.56]$, $p = 0.038$) and weight effect ($F(1, 11) = [14.18]$, $p = 0.003$) (**Figure 2.9**). The outcome of increased task completion time due to these factors was almost similar in the tripod pinch and tip pinch, with the tip pinch conditions generally requiring a higher task completion time.

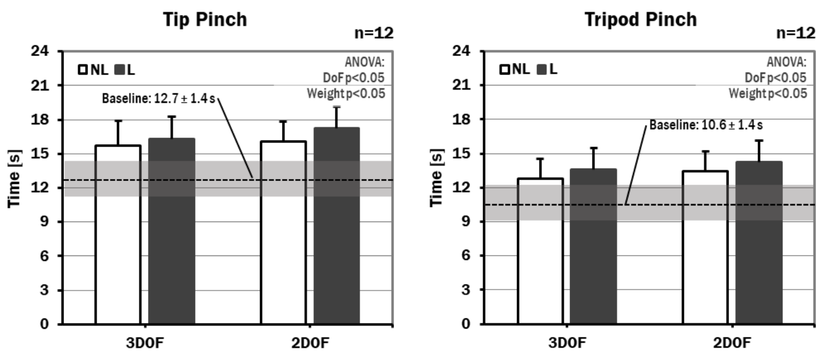


Figure 2.9 Task completion time result (lesser values are better).

2.3.2 Perceived Ease of Performing the Task

Dunnett's test indicated a significantly lower rating while wearing the HE, except for the condition with three DOF without the load (3DOF NL), compared to that at baseline. Furthermore, based on ANOVA, both DOF ($F(1, 11) = [6.62]$, p =

0.026) and weight (F(1, 11) = [26.61], p ≤ 0.001) showed a significant effect on the rating of the perceived ease of performing the task using tip pinch (**Figure 2.10**). In these results, both DOF reduction and weight addition resulted in lower ratings. Meanwhile, specifically for the tripod pinch (**Figure 2.10**), it was shown that the main effects were followed by a significant interaction effect (F(1, 11) = [8.05], p = 0.016), in which the rating drop due to weight addition was steeper in the 2DOF than in the 3DOF.

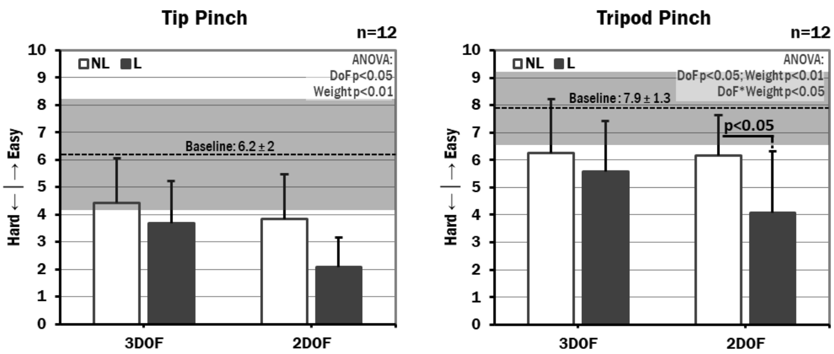


Figure 2.10 Perceived Ease of Performing the Task

2.3.3 ROM Reduction of Digits' Joints

From the 39 separate analyses using ANOVA (**Table 2.3**), twenty significant main effects and six interaction effects were found. These results revealed a similar pattern of factors and interaction effects between the tip and the tripod pinch. For both types of pinches, there was no significant effect on the thumb IP and the index finger DIP joint, and the significant effects were found more dominant in the finger(s) than in the thumb. However, the tripod pinch showed a greater distribution of the significant effects on the middle finger than that on the index finger.

Table 2.3. The P(T ≤ t) two-tailed value of two-way repeated measure ANOVA of ROM reduction affected by the DOF and weight (Wt.); **(a)** at tip pinch; **(b)** at tripod pinch.

	(a) at tip pinch			**(b)** at tripod pinch		
	Insertion Depth			**Insertion Depth**		
	6 mm	**12 mm**	**18 mm**	**6 mm**	**12 mm**	**18 mm**
Thumb MCP						
DOF	0.242	0.096 *	0.149	0.842	0.081 *	0.757
Wt.	0.433	0.316	0.995	0.494	0.929	0.580
DOF×Wt.	0.554	0.985	0.990	0.695	0.044 **	0.245
Thumb IP						
DOF	0.762	0.516	0.176	0.695	0.930	0.791
Wt.	0.524	0.124	0.514	0.251	0.902	0.474
DOF×Wt.	0.420	0.534	0.362	0.686	0.624	0.395
Index MCP						
DOF	0.932	0.212	0.049 **	0.544	0.461	0.598
Wt.	0.996	0.350	0.912	0.256	0.133	0.362
DOF×Wt.	0.056 *	0.905	0.457	0.117	0.211	0.006 **
Index PIP						
DOF	0.001 **	0.005 **	0.001 **	0.011 **	0.071 *	0.053 *
Wt.	0.567	0.323	0.405	0.366	0.188	0.084 *
DOF×Wt.	0.307	0.847	0.616	0.913	0.876	0.798
Index DIP						
DOF	0.816	0.416	0.409	0.793	0.892	0.254
Wt.	0.357	0.104	0.961	0.652	0.703	0.506
DOF×Wt.	0.244	0.719	0.521	0.501	0.456	0.240
Middle MCP						
DOF				0.477	0.396	0.228
Wt.				0.036 **	0.006 **	0.090 *
DOF×Wt.				0.319	0.030 **	0.016 **
Middle PIP						
DOF				0.002 **	0.016 **	0.006 **
Wt.				0.211	0.051 *	0.076 *
DOF×Wt.				0.268	0.546	0.191
Middle DIP						
DOF				0.501	0.248	0.112
Wt.				0.647	0.093 *	0.032 **
DOF×Wt.				0.121	0.625	0.043 **

* $p < 0.1$ ** $p < 0.05$

At the tip pinch (**Table 2.3.a**), no weight effect was observed in all the digit joints, and only a few signs of the DOF effect were observed in the thumb MCP joint. Meanwhile, the DOF had a significant effect on the ROM reductions of the index finger PIP joint for all the peg insertion depths, with the highest increase of 3.92 times seen at the 6 mm peg insertion depth for conditions without the load (**Figure 2.11**). At this joint, no interaction was found between DOF and weight. Further, we found that the lower the DOF, the higher the ROM reduction, as shown in **Figure 2.11**.

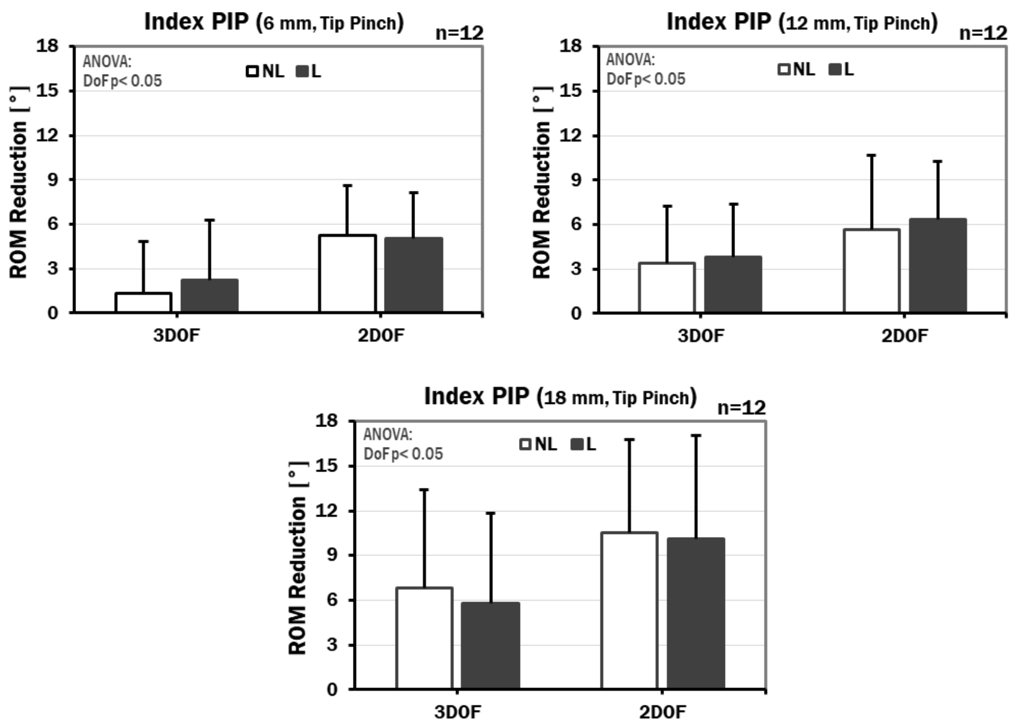
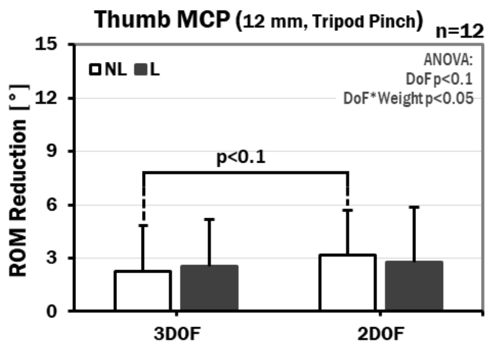


Figure 2.11 ROM reduction of the Index PIP joint.

At the tripod pinch (**Table 2.3.b**), both DOF and weight showed a significant effect on more joints, and some significant main effects were even followed by significant interaction. For example, at the 12 mm peg insertion depth, at the thumb MCP joint, the DOF effect was followed by a significant interaction effect (**Figure 2.12.a**) thus making the ROM reduction increase by 0.9° or 41.9%

in the conditions without load. Just like the tip pinch, the DOF reduction causes a significant ROM reduction increment in the index finger PIP joint at all the peg insertion depths, without being followed by interaction effects (**Table 2.3.b**). However, a more significant increment of ROM reduction up to >3° is observed in the middle finger PIP joint at the 6 mm and 18 mm peg insertion depths (**Figure 2.12.b**), while at the 12 mm insertion, there was no significant difference even though it had a similar trend.

(**a**)



(**b**)

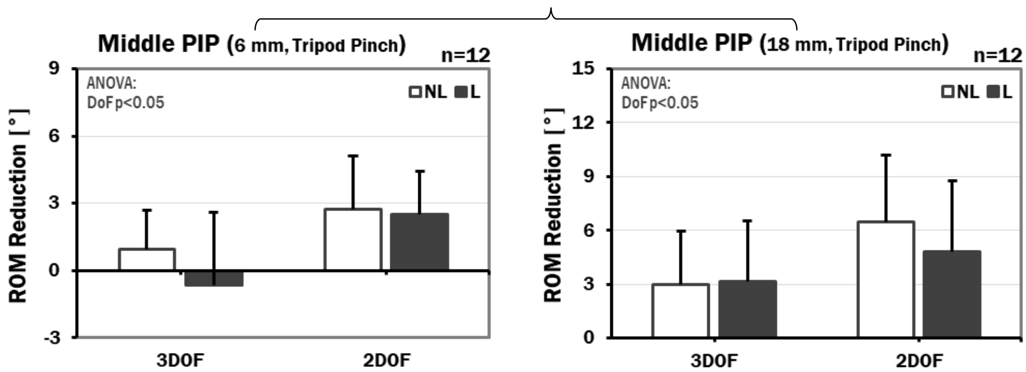


Figure 2.12 ROM reduction of joints affected by the degree of freedom reduction for insertion using tripod pinch; **(a)** at the thumb MCP joint; **(b)** at the middle finger PIP joint.

In contrast to the DOF reduction effect, the weight addition effect in the tripod pinch (**Figure 2.13**), commonly produced ROM reduction correction.

Moreover, the effect of weight addition was more significant in the two DOF conditions. In **Figure 2.13.a**, a 15.7% correction of ROM reduction ($p < 0.1$) due to weight addition is found after further exploration of the significant interaction effect at the index finger MCP joint. Significant weight addition effects followed by significant interaction effects were also indicated at the middle finger MCP joint. At this joint, ROM reductions were lower at 2 DOF compared to 3 DOF with correction by up to 0.9° or 29% at 12 mm peg insertion (**Figure 2.13.b**). At the middle finger DIP joint, the correction was even greater, up to 3.8°, thus making the ROM at the same level as the baseline (**Figure 2.13.c**).

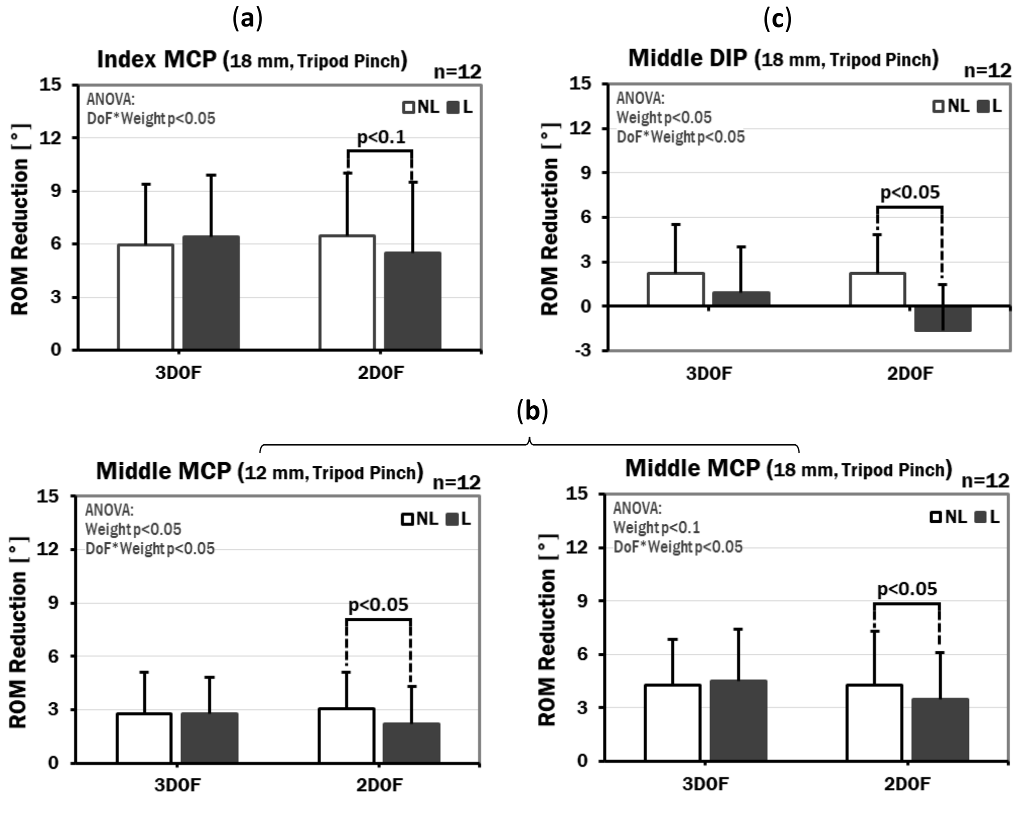


Figure 2.13 ROM reduction of joints affected by weight addition for insertion using tripod pinch; **(a)** at the index finger MCP joint; **(b)** at the middle finger MCP joints; **(c)** at the middle finger DIP joint.

2.4 Discussion

This study aims to investigate the effects of the HE DOF and weight on the hand joint mobility function in performing fine hand use activities that were measured through task completion time, perceived ease of performing the task, and the ROM. The changes in productivity, perceived ease, and ROM that have been found need to be further discussed.

2.4.1 Effect of Wearing HE

Both productivity and perceived ease of performing the task were significantly affected by wearing the HE. With this result, it can be stated that wearing the HE reduced one aspect of joint mobility function, namely the ease of movement. The unavoidable consequences of wearing an HE, such as movement restriction or overall hand weight increase, were suspected to be the cause of this reduction in performance. This result is in line with that of other studies regarding the effect of movement restriction on hand (Bensel, 1993; Rodinelli et al., 1997; Wells et al., 2010). However, based on the subjective evaluation results (**Figure 2.8**), wearing an HE while performing the tasks was not perceived as difficult, as long as the task was not too precise (performed with the tripod pinch), and the participant did not wear the 2DOF L setup (heavy and involving high resistance). These findings are in agreement with a study of a rigid type HE, with which the user expressed feelings of ease (Almenara et al., 2015). This result showed that the HE has the potential to become more comfortable to wear while performing certain fine activities by adjusting some design parameters, even though in general, wearing the HE would reduce productivity.

2.4.2 Effect of DOF

Due to the pushrods in the exoskeleton, the segments are restricted to moving in tandem with one another for 2DOF and 3DOF, as shown in **Figure 2.3**. Our results demonstrated that the degree of restriction significantly affects the ease of movement for both the tip and the tripod pinch (**Figures 2.9** and **Figure 2.10**). This is consistent with the results of Rodinelli et al. (1997), where the application of splints to hand joints significantly reduced productivity. However, in **Table 2.3**, it is shown that the effect did not occur at every joint. The DOF effects were significant only at the PIP joint for all the insertion depths.

The 2DOF setup used in this study imposed potential movement restrictions due to the medial push rod. Eventually, the finger ROM is reduced as shown in **Figures 2.11** and **Figure 2.12**. The PIP joint naturally has higher mobility compared to the MCP and DIP joints when performing gripping action (Jo et al., 2019), making it easily disturbed by external factors that inhibit motion. **Figure 2.11** is consistent with this DOF effect since the two DOF linkage systems used in this study regulated the motion of the PIP joint more than the other joints. Predictably, the DIP joint was the only joint that was not affected by DOF reduction, since its ROM is the smallest.

On the other hand, the impact of DOF reduction on insertion tasks could be accomplished with opposable thumb presents, the abduction/adduction of fingers could be maintained, as well as wrist flexion/extension movements (Montagnani, Controzzi, & Cipriani, 2016). Meanwhile, movement stability during a decrease in finger movement was achieved via the thumb, as their opposed movement partner

(**Table 2.3.a**, **Table 2.3.b**, and **Figure 2.12.a**). However, the effect was less noticeable since the ROM of the thumb joints is smaller than that of the fingers and it did not affect the success of performing the task.

In the end, it can be stated that first, the negative effect of the DOF reduction occurred in any condition, with any speed, and at any level of precision; second, the decrease in joint mobility function due to the DOF reduction would be most imposed on joints that had a large ROM and were directly regulated by the linkage system, and third, there was no noticeable compensation on the other digits' joints due to PIP ROM reduction, and this did not interfere with task completion.

2.4.3 Effect of Weight

Figure 2.9 shows that weight addition on HE digits causes a significant increase in task completion time. This could be due to the increase in weight causing a higher demand for movement control from the hand-arm muscles, especially when high acceleration or deceleration is required (Yoon, Shiekhzadeh, & Nordin, 2012). This simulates the decrease in hand movement performance when a heavy glove is worn (Wells et al., 2010). From a mechanics point of view, slowed hand performance occurs because the increased hand inertia tends to resist changes in motion direction which ultimately makes it difficult to control. Difficulty in controlling the movement will interfere with the mobility function, eventually reducing hand dexterity.

Besides productivity, the rating of perceived ease of performing the task was also lowered by weight addition (**Figure 2.10**). The effect was even stronger than DOF reduction with a $p < 0.01$ significant level. The possible cause of this result was that the subjective evaluation was aimed at not only the productivity task but also the motion tasks. Therefore, it is related to the longer task duration of the use of the HE, in which the weight addition psychophysically affected the capacity limit of the user (Ciriello et al., 1990), especially if the user had not gotten used to it.

From the result of the dexterity test and subjective evaluation, it can be said that the HE's weight affects hand joint mobility function in terms of its ease of movement. Additionally, the psychophysical effect of weight may occur when the heavy HE is worn for a long duration during early use.

2.4.4 Interaction Effect

Significant interaction effects between the DOF and weight were found at tripod pinch. In **Figure 2.10**, the effect of weight works differently between 3DOF and 2DOF. This figure shows that a massive rating drop occurs when the 2DOF setup is applied. At this pinch type, not only is the rating significantly different but it also jumps down from easy to difficult (from 6 to 4). The possible cause of this occurrence is that the preserved flexibility in 3 DOF might have been allowing the hand to perform better and be perceived as much easier to move, even though the weight had been increased. The preserved flexibility was also described as the cause of better performance in a proposed protective gloves design (Dianat, Haslegrave, & Stedmon, 2014).

A critical finding of the interaction effect was presented in the motion analysis results. In **Table 2.3**, the interaction occurs at the MCP and DIP joints and has never been indicated at the PIP joint. As reported by Jo et al. (2019), the MCP and DIP joints have a relatively lower ROM than the PIP joints during gripping and manipulation. This means that the interaction is more likely to occur at the lower ROM joints. Moreover, this intervention frequently follows the significant weight effect, and the effect is positive for ROM (**Figure 2.13**). Interestingly, the significant difference due to these effects mostly occurs at the two DOF. A possible explanation is that the linkage resistance of the 2DOF setup is greater than 3DOF, where the assistance against the motion resistance upon an increase in weight becomes more meaningful.

The possible cause of the recovered ROM due to weight addition at 2 DOF is the gravitational advantage of the downward peg insertion. This assumption is based on the proof that aligning the direction of force with gravity can be used as a method to improve the ROM (Khallaf, 2018), and it has even been used as a principle in manual working (Boothroyd, Dewhurst, & Knight, 2019). The force produced by the load's mass and gravity successfully assisted the peg insertion motion despite the high movement resistance of 2 DOF linkages. Lastly, comprehensive assistance is important for peg insertion because it requires both flexion and extension. In this case, this force successfully accommodated both, meaning it was great enough to assist the insertion (downward) and small enough to not resist the motion when the direction was reversed (upward).

At this point, it can be stated that the weight addition at 2 DOF brought a positive effect on the movement range of the joint mobility function. Gravity and appropriate weight addition play an important role in making this happen. However, digit weight has become an increasingly important factor in this setup, and it requires careful consideration in its management.

2.4.5 Design Direction

Lightweight and high DOF are the most ideal design characteristics of an effective HE for daily life activities. However, a strong and simple device with these characteristics is difficult to design due to technical and technological reasons. Therefore, based on our findings, we formulated a compromise strategy to design a more effective HE.

Choosing between 3 and 2 DOF fingers requires careful consideration because each has its advantages and disadvantages. When a high-performance HE system is required or high power is important, 2 DOF is recommended because it can distribute the power to two segments with a single actuator. We could try to reduce the negative effect of this choice (movement resistance) by using a flexible material (Mohammadi et al., 2018) for improving the ROM of the PIP joints or unfixing some digit joints (In et al., 2011); however, that might come at the expense of decreased mechanical stability (Cempini et al., 2014)

Considering the role of gravity in two DOF, it seems beneficial for a HE to provide a small force for counterbalancing movement resistance in addition to its main force for gripping assistance. The implementation of this idea needs a creative process such as “separation” as a solution to the physical contradiction that might occur (Yang & El-Haik, 2008). In this case, separation can mean the use of two different types of actuators for two different purposes or two different control systems with different sensor sensitivity. However, it should be noted that these methods have the potential to increase the design complexity of the HE.

2.4.6 Limitation and Future Study

This study has several limitations. In general, the HE aims to improve hand function, regardless of age, sex, or disability. However, in this study, we only recruited adult male participants with normal hand function. On the other hand, fine hand use activities in daily life involve various types of objects when performing various tasks. However, the tasks in this study were still only for handling the peg (simple cylindrical object) and performing the pegboard tests with only two levels in each factor included.

It has been found that the ROM is improved due to a force that can counterbalance the movement resistance. However, in this study, the force is the consequence of the digits' weights that were assisted by the direction of gravity. This advantage can be expanded by providing a counterbalancing force from an external source such as active actuators. Hence, we suggest future studies that use a power-assisted HE prototype with an adjustable actuation force. In the case of measuring the various object manipulation task, motion measurement methods other than camera-based (not affected by the object blocking), such as the use of the IMU (inertial measuring unit) module (Glowinski et al., 2021; Mennella et al., 2022) are a potential option.

2.5 Conclusion

In general, wearing an HE reduces the mobility function especially when a lower DOF setup is applied. However, the weight addition may improve the movement range aspect of the function. Additionally, managing the digit's weight becomes increasingly important when the low DOF concept is considered. Considering the movement restriction generated by the HE mechanical system, the counterbalancing force might be a potential solution, and a further study of its characteristics is needed.

This study emphasizes the basic needs of an HE as a wearable assistive device that is light and flexible (has a high DOF). However, when heavy systems and low DOF are unavoidable, overcoming motion barriers becomes an important requirement. Based on the findings in this study, the usage of a counterbalancing force that works either passively or actively becomes a recommendation. This is a differentiator from the general HE design strategy which tends to apply advanced materials or design concepts based on unfixed joints.

Chapter 3

Effects of Counterbalancing Force of The Hand Exoskeleton on Hand Joint Mobility Function

3.1 Introduction

Hand exoskeleton (HE) might provide a solution for improving hand function (Ferguson, Shen, & Rosen, 2020). However, providing an HE capable of assisting with daily activities remains the greatest challenge (Noronha & Accoto, 2021). Fine hand use activities occupy half of the daily hand activities (Vergara et al., 2014) thus consideration of fine hand use performance, especially in maintaining hand joint mobility of the user, is important for developing an assistive hand exoskeleton (HE). Because most of the assistance purposes HE adopts a linkage mechanism (Bos et al., 2016), mechanical characteristics, such as friction, inertia, and degree of freedom (DOF) reduction will be the main barrier to hand movement. In the fine hand use activities, Chapter 2 confirmed that most of the mechanical factors, especially friction, due to the installation of the linkage system of the HE reduce hand joint mobility.

A strategy to compensate for friction through the enhancement of the mechanical system of the HE is essential since the mechanical system plays an important role in a well-performing HE (Bianchi, 2020). In Chapter 2, it was found that weight addition of the HE digits may improve joint mobility. In that chapter, it is explained that the additional weight and the gravitation produce a force that can successfully counter the mechanical factors of the HE that was obstructing the digits' motion. It is also explained that when the movement direction was reversed, the force does not provide significant resistance to the motion. This weight force seems to act as a passive counterbalance. Passive counterbalancing has been used in the robotics field (Whitney & Hodgins, 2014; Song & Song, 2016). Not only mass or weight but spring mechanism also potential for producing passive counterbalancing force (Lee, Kim, & Song, 2022).

The application of a passive counterbalance for the HE has some drawbacks. Counterbalancing with preinstalled loads only works when the motion is in line with the direction of gravitation. Meanwhile, the hand activity is rich in variations that make movement can occur in any direction. On the other hand, counterbalancing with the spring mechanism may increase the design complexity of the HE. This creates difficulties because the rigid HE design is already complex due to actuators and linkage mechanisms (Sandoval-Gonzalez et al., 2017). Furthermore, tunning of the loads' weight or the spring force might also become troublesome because they might implicate parts replacement. Moreover, both of them can increase the total weight of the HE which eventually might bring a negative impact on hand joint mobility (Bensel, 1993).

Active counterbalancing has been applied in mechatronic systems for decades. The counterbalancing force is produced by actuators that are currently installed on the HE while friction compensation logic is included in the actuator control algorithm. This method cannot fully counter the friction, but the compensation result is promising (Schabowsky et al., 2010; Wang, Li, & Zeng, 2014). There might be an increase in design complexity due to the sensors but considering their lightweight compared to other components (Chen & Pomalaza-raez, 2010), the total weight of the HE remains unchanged. Moreover, counterbalancing force setup through a control algorithm is relatively simple than tunning the weight of the digits or adjusting the spring rate. However, in a simple active counterbalance system with one force sensor per digit utilized, the counterbalancing only works in one direction (only supporting flexion or extension) as the effect of finger loads in Chapter 2 thus the optimum force is required.

It is confirmed in Chapter 2 that underactuated through a linkage mechanism creates motion resistance. The resistance does not only occur due to regulated motion as a consequence of DOF reduction but also more friction sources due to a link installation. A system with higher friction requires a higher force for compensation (Wang, Li, & Zeng, 2014). On the other hand, in a linkage mechanism, any forces are distributed to all mechanically connected segments (Holowenko, 1955), including the counterbalancing force. For example, if the medial phalanx is interdependent with the proximal phalanx, the counterbalancing force is distributed to those both phalanxes. This distribution might streamline the effect of the counterbalance which causes an improvement in the mobility of more joints. Consequently, the distribution raises the required force which might resist the reverse movement. Furthermore, activities that require joint movements that are not in harmony with the predesigned motion of the interdependent mechanisms will be hampered.

Considering the potentiality of the active counterbalance application of an HE in improving joint mobility of the user's hand, an in-depth user interaction study is required. Therefore, this study aims to investigate the effect of the counterbalancing force of the hand exoskeleton on hand joint mobility function. This study includes the investigation of the effect of DOF reduction considering its role in distributing the counterbalancing force. This investigation focuses on the pinch as the most precision grip type in fine hand use activities. Active HE prototypes featured with adjustable DOF and counterbalancing force are required to achieve the objective. Several participants would use this prototype to perform motion tasks that measure the digits' joint range of motion, angular velocity, and angular acceleration. In addition, the perceived ease of performing the tasks would be rated. The results would represent the hand joint mobility (the ease of movement and the movement range) which later would be analyzed and discussed. Based on our findings, a design direction regarding counterbalancing force exertion would be proposed.

3.2 Materials and Methods

3.2.1 Participants

Eight males, with a mean age of 27 ± 4 years, were recruited as experiment participants. All participants were right-hand dominant, tested by The Edinburgh Handedness Inventory (Oldfield, 1971). The non-dominant hand (186 ± 17 mm hand length) was confirmed to be free of health issues and fatigue from recent strenuous hand activity. All participants provided written informed consent for the experiment, and the experiment has been approved by the Research Ethics Committee of the Faculty of Design, Kyushu University (approval number 329).

3.2.2 Prototypes

Three-digit prototypes from the previous study (**Figure 2.2.a**) were prepared. They were modified into active HE by installing a linear actuator (Actuonix Motion Devices Inc., Saanichton, BC, Canada) in each digit. A linear actuator is used to push each digit with a constant counterbalancing force. The actuator is installed on the actuator mounting that can be moved forward-backward freely in their slideway to accommodate fast digits flexion motion. When an actuator mounting reaches the end of its slideway (due to actuator elongation), the actuator is started to exert the counterbalancing force to its driven digit. The magnitude of the counterbalancing force is limited by the back drive force (reaction of the counterbalancing force). This back drive force is measured by the RP-S5-ST Force Sensitive Resistor (LEGACT, China) installed on the end part of the slideway. When the back drive force increases beyond a preset value, the actuator will pull the driven digit to follow the extension motion. Otherwise, the actuator pushes the digit to assist flexion motion. The actuator and sensor placement are presented in **Figure 3.1**.

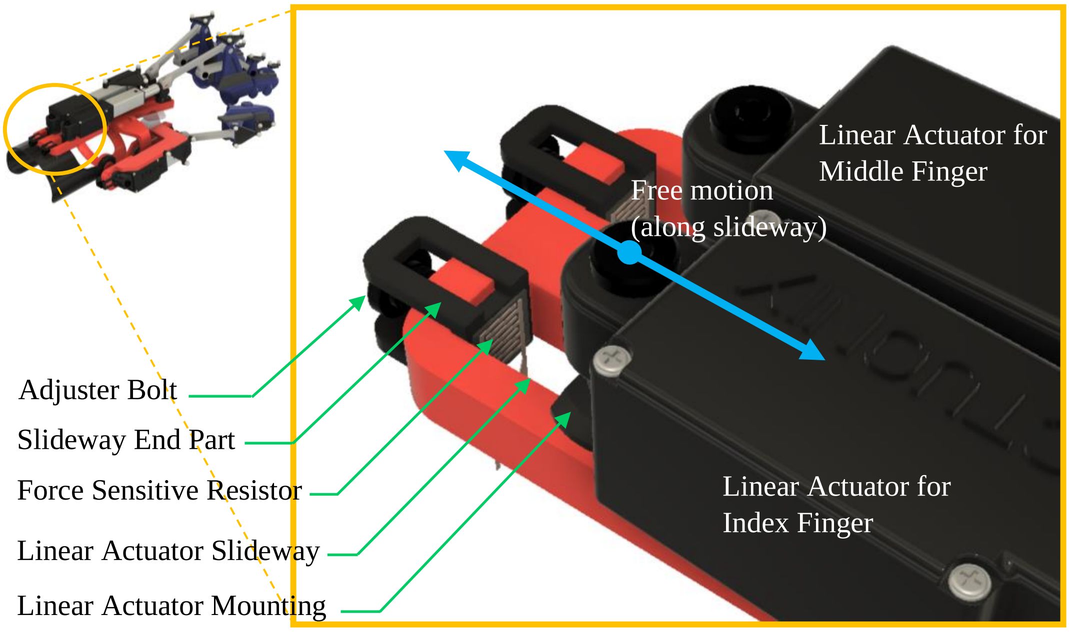


Figure 3.1 Linear actuator and force sensor placement of the hand exoskeleton.

Three channel controller was used to operate the three linear actuators. Each channel is possible for independent counterbalancing force setup by operating the selector knob. All controller units including the actuator drivers are placed in a controller box with a 12-volt battery power supply. Cables are used to connect the controllers to actuators and sensors. On the other hand, the digit components are detachable units for easy-wearing purposes. The digit component has a similar design to the previous study (Chapter 2) except for additional Velcro straps on the proximal and medial phalanx (for the thumb only on the proximal phalanx). The straps are utilized to improve the digit attachment against the counterbalancing force. The system of the prototype is presented in **Figure 3.2**.

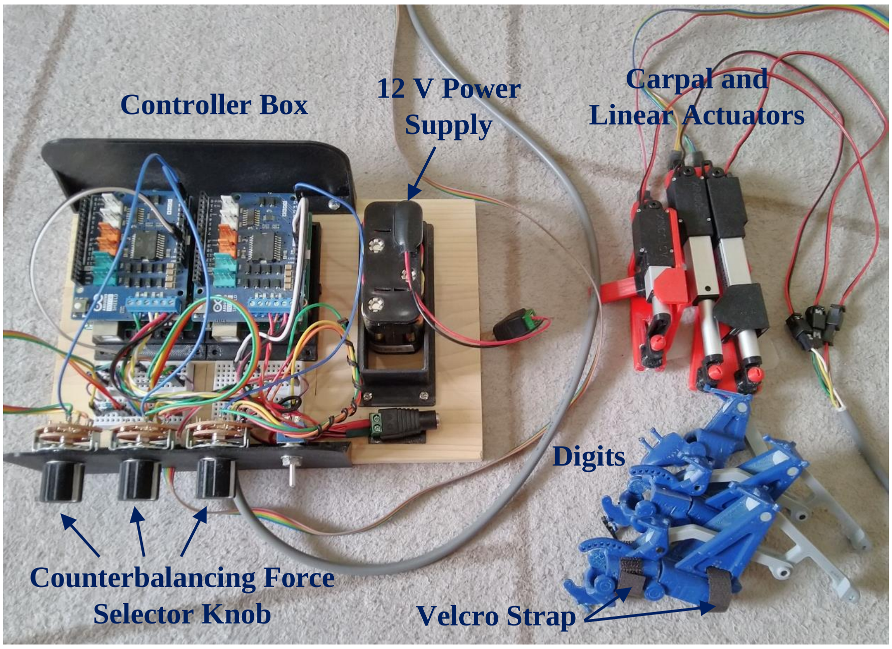


Figure 3.2 System of the hand exoskeleton prototype

For motion capture purposes, 25 retro-reflective markers with Ø4 mm (Nikon, Japan) were attached to the prototypes. The marker's name and position are similar to the study in Chapter 2 without the three markers on the forearm and arrangement for barehand conditions. The three markers on the forearm were not attached because the actuators and sensors cable require a clear area on the forearm. The attachment technique of markers (using a marker base) was also similar to the previous study (Chapter 2). Without studying barehand conditions, the marker bases were strongly stuck on the prototype so that they are more durable for longtime use during the experiment. The arrangement and the list of markers on the prototype are shown in **Figure 3.3**.

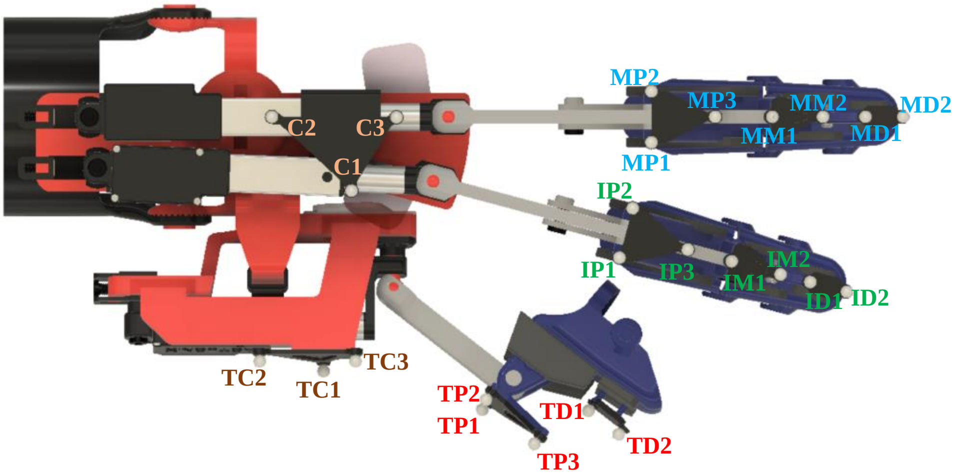


Figure 3.3 Arrangement and list of markers on the prototype.

3.2.3 Experiment Task

A motion task designed to measure the motion parameters of the hand joints (similar to the motion task in Chapter 2) was used. Two customized pegboards were prepared for this task in two sizes, namely Ø6.4 mm peg designated for two-finger pinch (tip pinch) and Ø20 mm peg for three-finger pinch (tripod pinch) (**Figure 3.4.a** and **Figure 3.4.b)**. The criteria for choosing the Ø6.4 mm peg was based on the original nine-hole peg test introduced by Mathiowetz et al. (1985), while that for the Ø20 mm peg was based on the proper size pinching object for the tripod pinch (Feix et al., 2016). Features, dimensions, and using procedure (**Figure 3.4.d**) of both pegboards and their peg (**Figure 3.4.c**) are similar to the pegboard used in the motion task in Chapter 2. An arm slider was also prepared to support the participant's forearm (**Figure 3.4.d**).

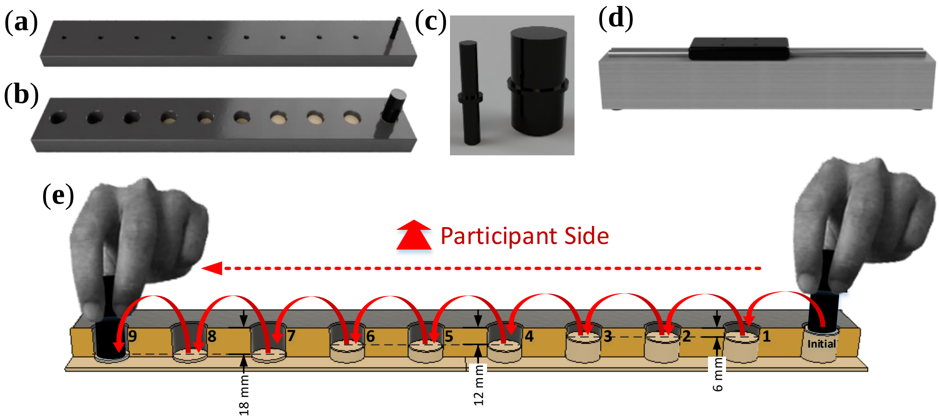


Figure 3.4 Customized pegboard test: (a) Ø6.4 mm pegboard for tip pinch; (b) Ø20mm pegboard for tripod pinch; (c) Ø6.4 mm and Ø20 mm peg; (d) the arm slider; (e) how to use the equipment.

3.2.4 Setup and Procedure

A dedicated space was prepared for the experiment. Generally, the experimental setup is similar to the motion analysis experiment in Chapter 2. The participant was made to sit on a chair in a comfortable upright posture while performing the task. The controller box was placed on a stool near the table. The pegboard was arranged according to the reach of the participant's left hand. The optimum position was achieved when the middle of the participant's body was in line with the position of target hole no. 7. The pegboard was placed on a 60 × 40 cm testing table while 10 near infra-red (NiR) cameras (Motion Analysis, Rohnert Park, CA) were arranged around the table. This participant position allowed an unencumbered view of the target hole, i.e., the exoskeleton did not impair visibility. The illustration of the experiment layout is presented in **Figure 3.5.a**, while the situation during the experiment is documented in **Figure 3.5.b** and **Figure 3.5.c.**

(a) (b)

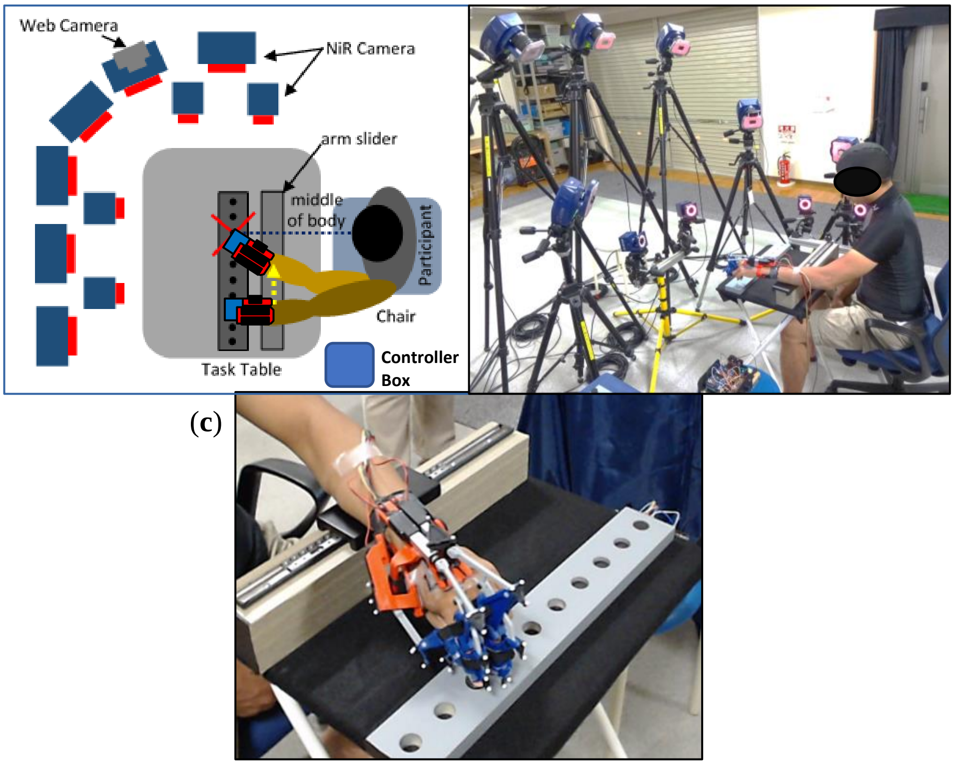


Figure 3.5 Experiment setup: **(a)** Experiment layout **(b)** Situation during the experiment **(c)** The HE up close: Performing the task with tripod pinch.

Six conditions based on the DOF and counterbalancing force setup (**Table 3.1**) and two conditions based on the type of pinch (the tip pinch and the tripod pinch) were used in this experiment. The six conditions based on the DOF and counterbalancing force setup were balanced using the Latin Square, whereas the pinch type conditions are balanced by reversing the execution order for half of the participants.

Table 3.1 Conditions based on HE and counterbalancing force setup.

Condition	**Annotation**
3DOF H	3 DOF index and middle finger, high counterbalancing force (100 g)
3DOF L	3 DOF index and middle finger, low counterbalancing force (30 g)

3DOF N	3 DOF index and middle finger, no counterbalancing force
2DOF H	2 DOF index and middle finger, high counterbalancing force (100 g)
2DOF L	2 DOF index and middle finger, low counterbalancing force (30 g)
2DOF N	2 DOF index and middle finger, no counterbalancing force

The experiment was conducted in a systematic protocol with preparation, HE set-up, counterbalancing force set-up, pegboard set-up, practice (with instruction), the task for both pinch types, and rest. For the task, the participants were asked to insert the peg until it touched the bottom of the holes, consecutively from hole no. 1 to 9 without adjusting the grip or releasing the peg (**Figure 3.4.e**). The participants were also instructed to perform the insertion motion as naturally and smoothly as possible. Each task was executed thrice, and the average result was calculated before the statistical analysis stage. While resting after completing the motion tasks with the same DOF and counterbalancing force setup, the participants were asked to rate the perceived ease of the condition that they had just experienced (for both the tip and tripod pinches).

3.2.5 Measurements

a. Digit Joints' Motion Parameters

For measuring the parameters, a motion capture system (Motion Analysis, Rohnert Park, CA, USA) was used. The recording rate was set to 100 Hz. The recorded marker position data have proceeded with the Cortex 7 software (Motion Analysis, Rohnert Park, CA, USA) to obtain continuous and clean motion data. Several virtual markers were added to allow the parameters to be measured in planar motion. The names and locations of the virtual markers on the HE are presented in **Figure 3.6**. The exact positions of the virtual markers, used to produce or approximate planar motion, may differ across participants.

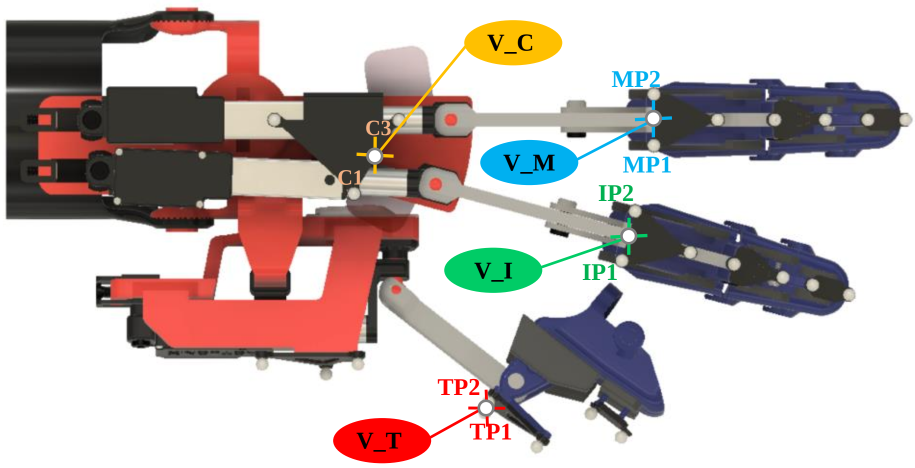


Figure 3.6 List and placement of virtual markers on hand exoskeleton.

The data of the digit joint angles for measuring the ROM were processed using the four-marker angles method. In this method, an angle is defined by two lines that are each constructed by two markers. **Table 3.2** below lists the digit joint angles and their forming markers.

Table 3.2. List of digit joints and forming markers.

Digit	Digit Joint	Four Marker Angles [Line 1, Line 2]
Thumb	T MCP (Thumb Metacarpophalangeal)	From V_T to TP3, From TC3 to TC2
	T IP (Thumb Interphalangeal)	From TD1 to TD2, From TP3 to V_T
Index Finger	I MCP (Index Metacarpophalangeal)	From V_I to IP3, From V_C to C2
	I PIP	From IM1 to IM2, From IP3 to V_I

	(Index Proximal Interphalangeal)	
	I DIP (Index Distal Interphalangeal)	From ID1 to ID2, From IM2 to IM1
Middle Finger	M MCP (Middle Metacarpophalangeal)	From V_M to MP3, From C3 to C2
	M PIP (Middle Proximal Interphalangeal)	From MM1 to MM2, From MP3 to V_M
	M DIP (Middle Distal Interphalangeal)	From MD1 to MD2, From MM2 to MM1

Three motion parameters were measured: The range of motion (ROM), the maximum value of angular velocity (max ω) or abbreviated as AV, and the maximum value of angular acceleration (max α) or abbreviated as AA of the joints. The ROM is defined as the difference between the maximum and the minimum digit joint angle which resulted from the activity of inserting a peg into a hole up to a certain depth: 6 mm, 12 mm, or 18 mm. Meanwhile, the ω is the change of joint angle over time. Then the α is the change of ω over time. AV and AA are the peak value that was observed along the insertion activity for a certain depth. Especially for AV, the analysis was separated for extension and flexion movement in which simultaneous joint movement of insertion (MCP flexion – PIP extension – DIP or IP extension) was the main concern of this study. As there are three consecutive holes with the same depth, the parameters were observed from the moment the peg reaches the bottom of the first hole until the peg reaches the bottom of the third hole. The determination of the moments was utilizing the Z position of the IM2 marker. **Figure 3.7** illustrates how the parameters of the index finger PIP joint (I PIP) while performing peg insertion on a 12 mm depth hole using tip pinch, with 2 DOF and low counterbalancing force set up, were determined.

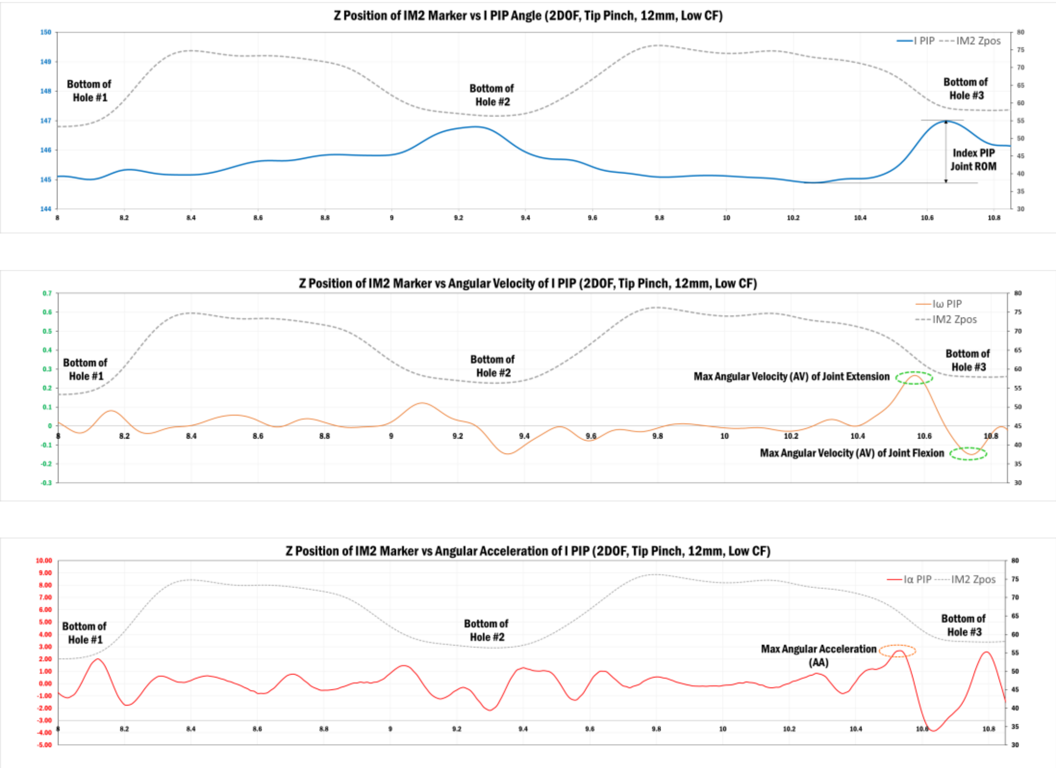


Figure 3.7 Example graph of ROM, angular velocity, and angular acceleration vs Z position of IM2 Marker.

b. Perceived Ease of Performing the Task

Right after the participants had a chance to experience what it was like to perform the tasks with the HE setup for both the pinch conditions (tip pinch and tripod pinch), they were asked to fill out a questionnaire about the perceived ease of performing a task. The questionnaire was rated on an 11-point scale, from 0 ("extremely hard to do") to 10 ("absolutely easy to do"), with 5 as the neutral point (neither hard nor easy). At each filling, the participant was asked to rate the perceived ease for each of the pinch types (the tip pinch and tripod pinch).

3.2.6 Statistical Analysis

Before processing with statistical tools, all data were checked for outliers (with Grubbs` Test) and missing values. All statistical analyses were conducted using open-source statistical software, Jamovi 2.2.2 (https://www.jamovi.org). Two-way repeated measures ANOVA was used to analyze the effect of the factors (DOF and counterbalancing force) on ROM, AV, and AA at the 0.1 and 0.05 significance levels. A Bonferroni corrected pairwise comparison post-test was used to further explore the significant main effect and significant interaction. The analysis was separated based on pinch type (tip pinch, tripod pinch), depth of peg insertion (6 mm, 12 mm, 18 mm), and digit joint (T MCP, T IP, I MCP, I PIP, I DIP, M MCP, M PIP, M DIP). Additionally, similar tools were used to analyze the perceived ease of performing the task with a 0.05 significant level, separated by the type of pinch (tip pinch, tripod pinch).

3.3 Result

3.3.1 Digit's Joints Range of Motion

Table 3.3. The P(T ≤ t) two-tailed value of two-way repeated measure ANOVA of ROM affected by the DOF and counterbalancing force (CF); **(a)** at tip pinch; **(b)** at tripod pinch.

	(a) at tip pinch			**(b)** at tripod pinch		
	Insertion Depth			**Insertion Depth**		
	6 mm	**12 mm**	**18 mm**	**6 mm**	**12 mm**	**18 mm**
Thumb MCP						
DOF	0.146	0.098 *	0.889	0.931	0.440	0.834
CF	0.138	0.451	0.909	0.032 **	0.481	0.836
DOF×CF	0.444	0.752	0.772	0.977	0.957	0.166
Thumb IP						
DOF	0.140	0.161	0.911	0.068 *	0.439	0.403
CF	0.797	0.209	0.543	0.666	0.392	0.264
DOF×CF	0.036 **	0.186	0.465	0.470	0.251	0.851
Index MCP						
DOF	0.113	0.488	0.213	0.699	0.077 *	0.073 *
CF	0.139	0.780	0.347	0.010 **	0.088 *	0.336
DOF×CF	0.188	0.590	0.386	0.436	0.554	0.318
Index PIP						
DOF	0.001 **	0.001 **	0.012 **	0.002 **	0.003 **	0.002 **
CF	0.828	0.981	0.569	0.953	0.801	0.463
DOF×CF	0.538	0.086 *	0.160	0.956	0.212	0.798
Index DIP						
DOF	0.181	0.775	0.313	0.070 *	0.234	0.393
CF	0.188	0.236	0.967	0.010 *	0.419	0.257
DOF×CF	0.359	0.333	0.362	0.360	0.417	0.256
Middle MCP						
DOF				0.692	0.112	0.547
CF				0.852	0.167	0.916
DOF×CF				0.667	0.087 *	0.095 *
Middle PIP						
DOF				0.008 **	0.004 **	0.006 **
CF				0.175	0.057 *	0.551
DOF×CF				0.087 *	0.640	0.826
Middle DIP						
DOF				0.021 **	0.098 *	0.771
CF				0.664	0.956	0.555
DOF×CF				0.642	0.579	0.425

* $p < 0.1$ ** $p < 0.05$

The 39 separate analyses using ANOVA (**Table 3.3**) found 21 significant main effects and five interaction effects. A significant main effect is rarely found at the thumb but found a lot at the middle finger (tripod pinch). No counterbalancing force and only one interaction effect were indicated at the tip pinch while when performing the tripod pinch the effect was dominant at 6 mm insertion. Interaction effects were mostly found on the middle finger but there were not many interaction effects in the overall analysis.

At the tip pinch (**Figure 3.8**), no significant counterbalancing force effect was found. Meanwhile, for the thumb (**Figure 3.8.a**), the DOF effect was observed on the MCP joint. The highest ROM due to low counterbalancing force exertion at the MCP joints was quite noticeable. However, since counterbalancing force effect was not significant, the indication doesn't lead there yet. Meanwhile, the IP joint (**Figure 3.8.a**) did not show any main effects. However, the interaction effect occurred as pattern variation (3 DOF vs 2DOF) among counterbalancing force conditions.

For the index finger (**Figure 3.8.b**) strong DOF effect was indicated on the PIP joint in which 3 DOF setups produce higher ROM than 2 DOF. Not only the main effects but there was also an interaction effect indicated by lower ROM difference (3 DOF vs 2 DOF) when the higher counterbalancing force was exerted. However, the difference looks similar between the low and high counterbalancing forces. On the other hand, for the MCP and DIP joint, no single effect was found.

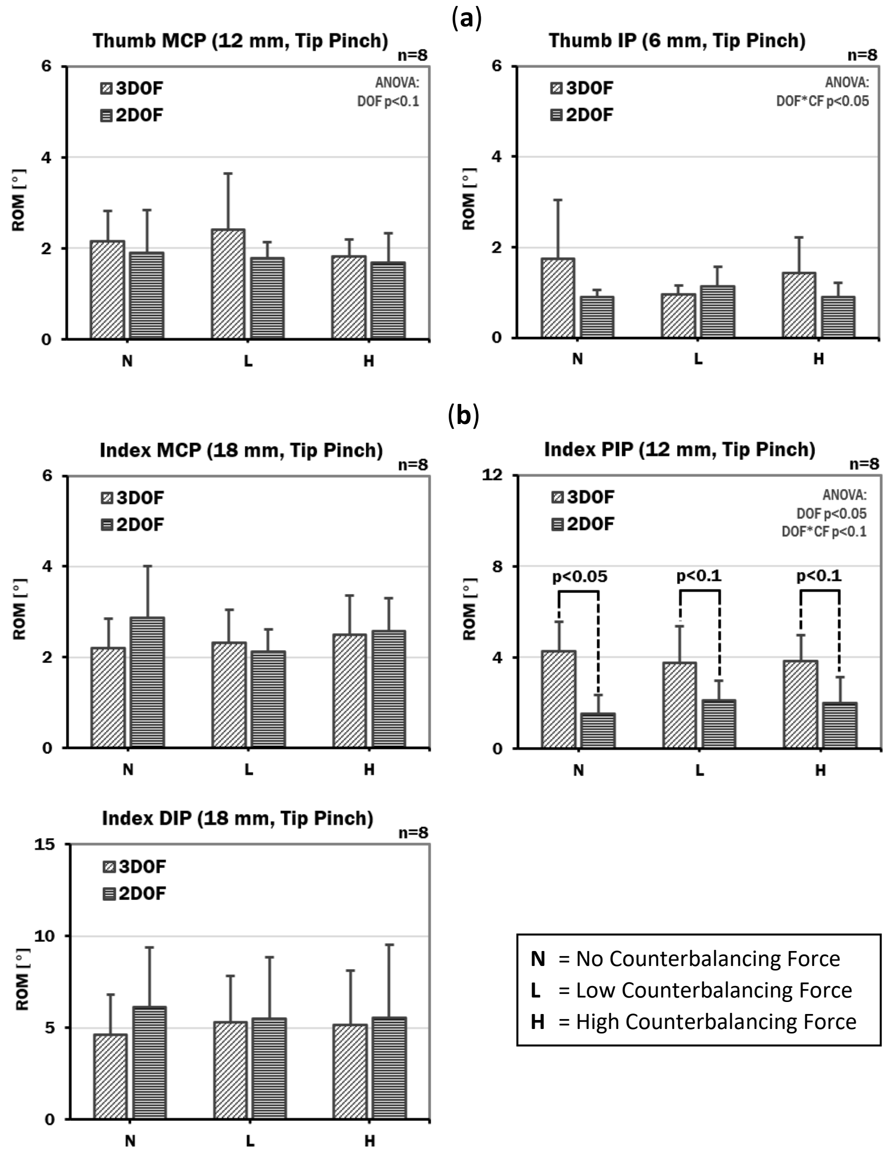


Figure 3.8 Counterbalancing force and DOF effect on ROM at tip pinch: **(a)** at the thumb; **(b)** at the index finger

The ROM measurement results of the tripod pinch (**Figure 3.9)** showed significant main effects on all digits. However, the effects varied on each digit. On the thumb (**Figure 3.9.a**), especially for the MCP joint, the significant effect of counterbalancing force was observed. However, it did not give enough indication of the ROM difference among the three counterbalancing force conditions.

Meanwhile, at the IP joint, the ROM is significantly affected by DOF reduction of the fingers. In this result, 3 DOF setups show higher ROM compared to 2 DOF.

For the index finger (**Figure 3.9.b**), a significant counterbalancing force effect was indicated on the MCP and DIP joint. This result shows that ROM is significantly reduced when a high counterbalancing force was exerted. Meanwhile, the result of the PIP joint presented a clear DOF effect in which the ROM dropped when the 2 DOF setup was applied. The DOF effect was also found at the DIP joint. However, the effect is the opposite with the PIP in which the ROM was improved when 2 DOF setups is implemented.

Different results are shown by the middle finger (**Figure 3.9.c)**. Significant main effects were found at PIP and DIP joints. At the PIP joint, a significant counterbalancing force was indicated in which the highest ROM was indicated at low counterbalancing force exertion. Along with it, a clear DOF effect was found in which the 2 DOF setup presented lower ROM. Meanwhile, DOF also affected on ROM of the DIP joint. However, the result shows the opposite from PIP in which the ROM was improved due to 2 DOF setups. On the other hand, the MCP joint did not indicate the existence of any main effect except for the interaction shown by the different patterns of DOF effect on ROM in each counterbalancing condition.

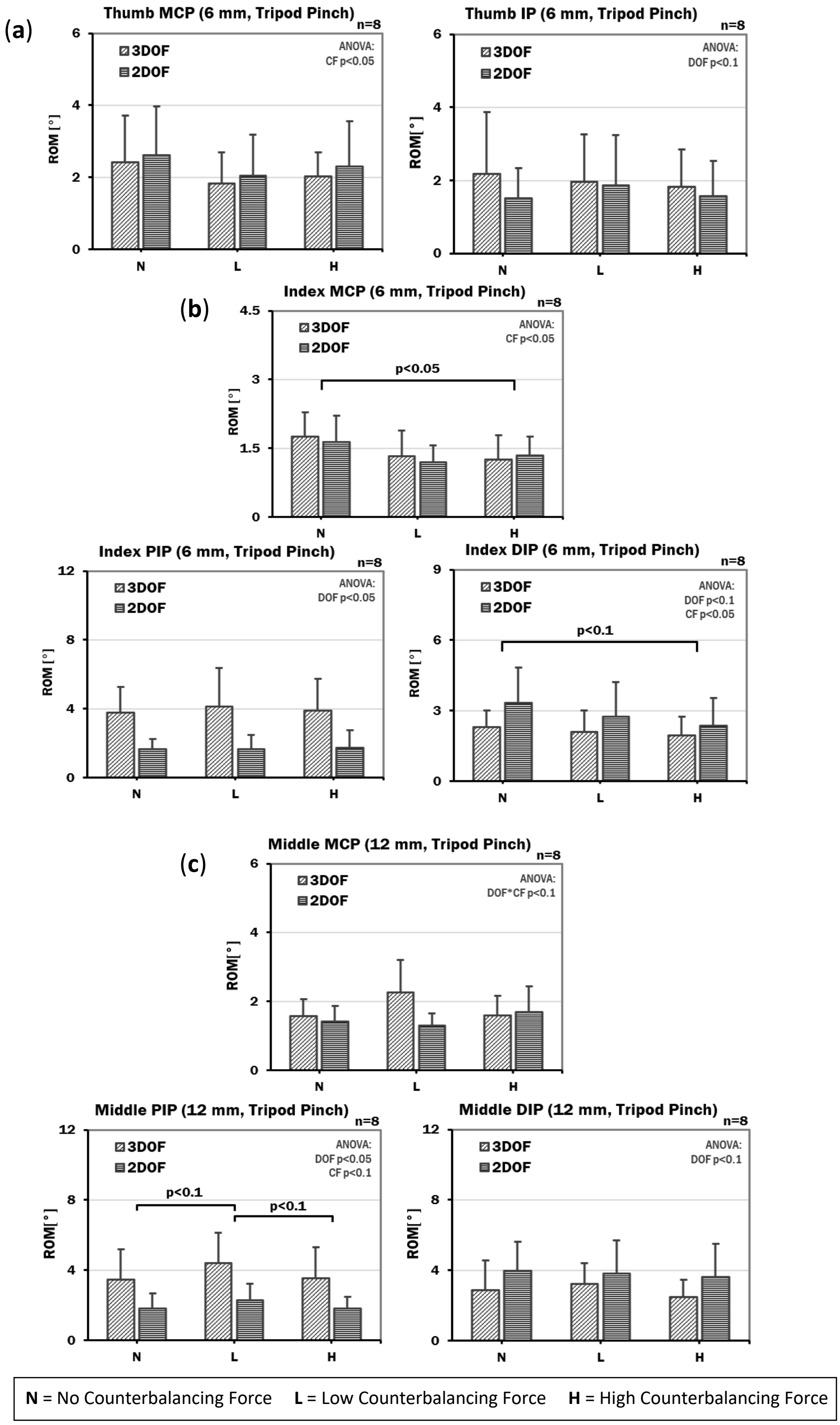


Figure 3.9 Counterbalancing force and DOF effect on ROM at tripod pinch: **(a)** at the thumb; **(b)** at the index finger; **(c)** at the middle finger.

3.3.2 Digit's Joints Angular Velocity

Table 3.4. The P(T ≤ t) two-tailed value of two-way repeated measure ANOVA of AV affected by the DOF and counterbalancing force (CF); **(a)** at tip pinch; **(b)** at tripod pinch.

	(a) at tip pinch			**(b)** at tripod pinch		
	Insertion Depth			**Insertion Depth**		
	6 mm	**12 mm**	**18 mm**	**6 mm**	**12 mm**	**18 mm**
Thumb MCP Flexion						
DOF	0.693	0.305	0.646	0.895	0.429	0.625
CF	0.386	0.019 **	0.708	0.044 **	0.391	0.861
DOF×CF	0.577	0.384	0.990	0.989	0.942	0.108
Thumb IP Extension						
DOF	0.157	0.269	0.886	0.032 **	0.461	0.925
CF	0.942	0.307	0.650	0.750	0.753	0.953
DOF×CF	0.076 *	0.271	0.781	0.600	0.462	0.780
Index MCP Flexion						
DOF	0.088 *	0.410	0.267	0.569	0.284	0.976
CF	0.436	0.389	0.925	0.415	0.654	0.019 **
DOF×CF	0.859	0.434	0.807	0.892	0.334	0.901
Index PIP Extension						
DOF	0.008 **	0.001 **	0.012 **	0.010 **	0.081 *	0.001 **
CF	0.382	0.981	0.193	0.403	0.984	0.011 **
DOF×CF	0.648	0.179	0.753	0.838	0.134	0.425
Index DIP Extension						
DOF	0.758	0.401	0.147	0.155	0.483	0.843
CF	0.956	0.498	0.402	0.329	0.718	0.515
DOF×CF	0.774	0.501	0.037 **	0.896	0.059 *	0.529
Middle MCP Flexion						
DOF				0.689	0.102	0.758
CF				0.792	0.072 *	0.053 *
DOF×CF				0.532	0.007 **	0.997
Middle PIP Extension						
DOF				0.031 **	0.046 **	0.001 **
CF				0.173	0.011 **	0.229
DOF×CF				0.391	0.855	0.696
Middle DIP Extension						
DOF				0.751	0.163	0.012 **
CF				0.023 **	0.316	0.630
DOF×CF				0.475	0.347	0.885

* $p < 0.1$ ** $p < 0.05$

The 39 separate analyses using ANOVA (**Table 3.4**) presented 18 significant main effects and seven interaction effects. Effects of DOF were mostly observed on the index finger PIP joint at both tip and tripod pinch. The AV on the thumb was less affected by counterbalancing force than the index finger at the tip pinch. Meanwhile, AV on the middle finger dominated the significant effect at the tripod pinch. At the tip pinch, the counterbalancing force effects were found on the thumb MCP joint while at the tripod pinch, the most affected joints were the index finger MCP and middle finger PIP joint. Finally, interaction effects were mostly found on the index finger at both the tip and tripod pinch.

The result of velocity measurement at the tip pinch (**Figure 3.10**) indicates the main effects and interaction effects on both the thumb and index finger. For the thumb, (**Figure 3.10.a**), a significant effect of counterbalancing force was found on the AV of the MCP joint. Further examination showed a significant difference in AV between the low counterbalancing force and the high counterbalancing force. It means the lowest AV was indicated when a high counterbalancing force was exerted. Meanwhile, the low counterbalancing force produces a high and consistent AV, but it has no significant difference with the condition of no exertion. On the other hand, although the main effect was not present on the IP joint, an interaction effect occurred which was indicated by an opposite pattern of AV between 3 DOF and 2 DOF. In this case, the low counterbalancing force exertion produced the highest AV when the 2 DOF setup was applied.

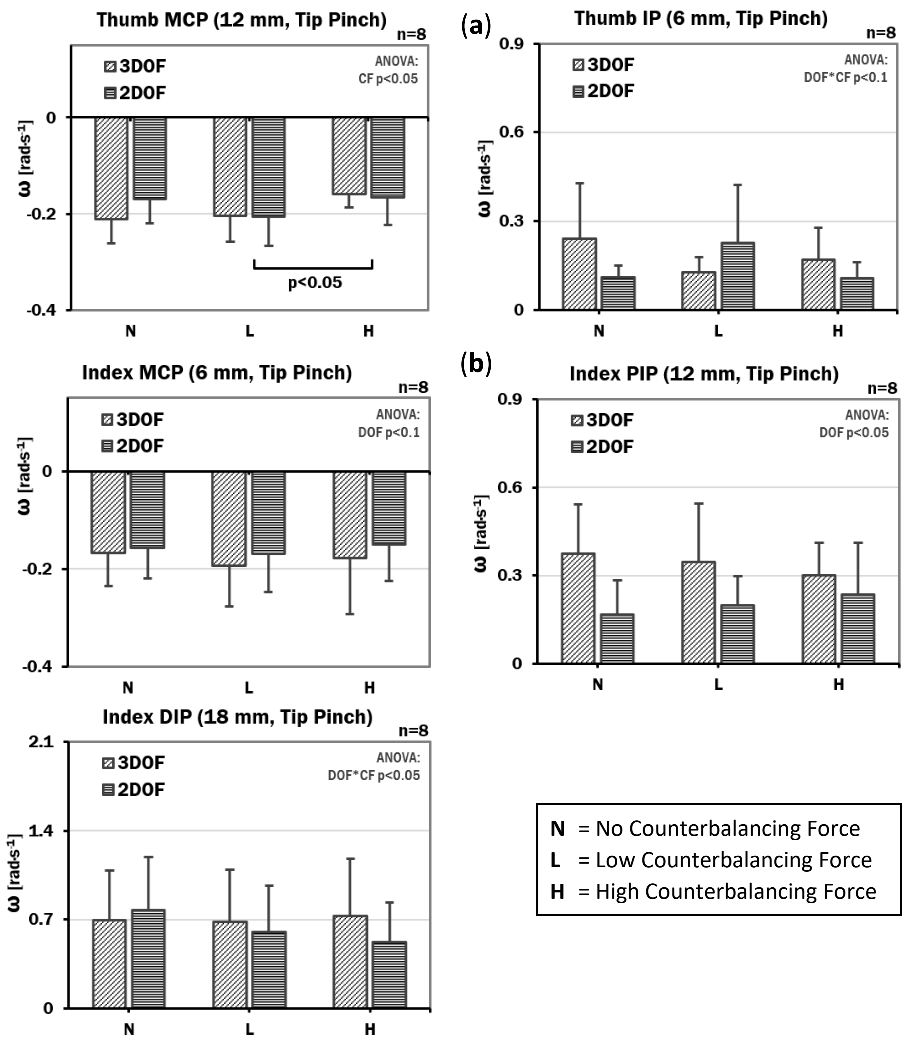


Figure 3.10 Counterbalancing force and DOF effect on the angular velocity at tip pinch: **(a)** at the thumb; **(b)** at the index finger

For the index finger (**Figure 3.10.b**), a significant DOF effect was indicated on the MCP and PIP joint. Especially for the PIP joint, the pattern shows the higher the counterbalancing force the less the AV difference between 3 DOF vs 2 DOF (similar pattern to **Figure 3.8.b)**. However, no interaction effect was presented. On the other hand, a significant interaction effect was found on the DIP without any main effect. The interaction occurs as indicated by an opposite AV pattern with the PIP joint. However, no significant difference was found.

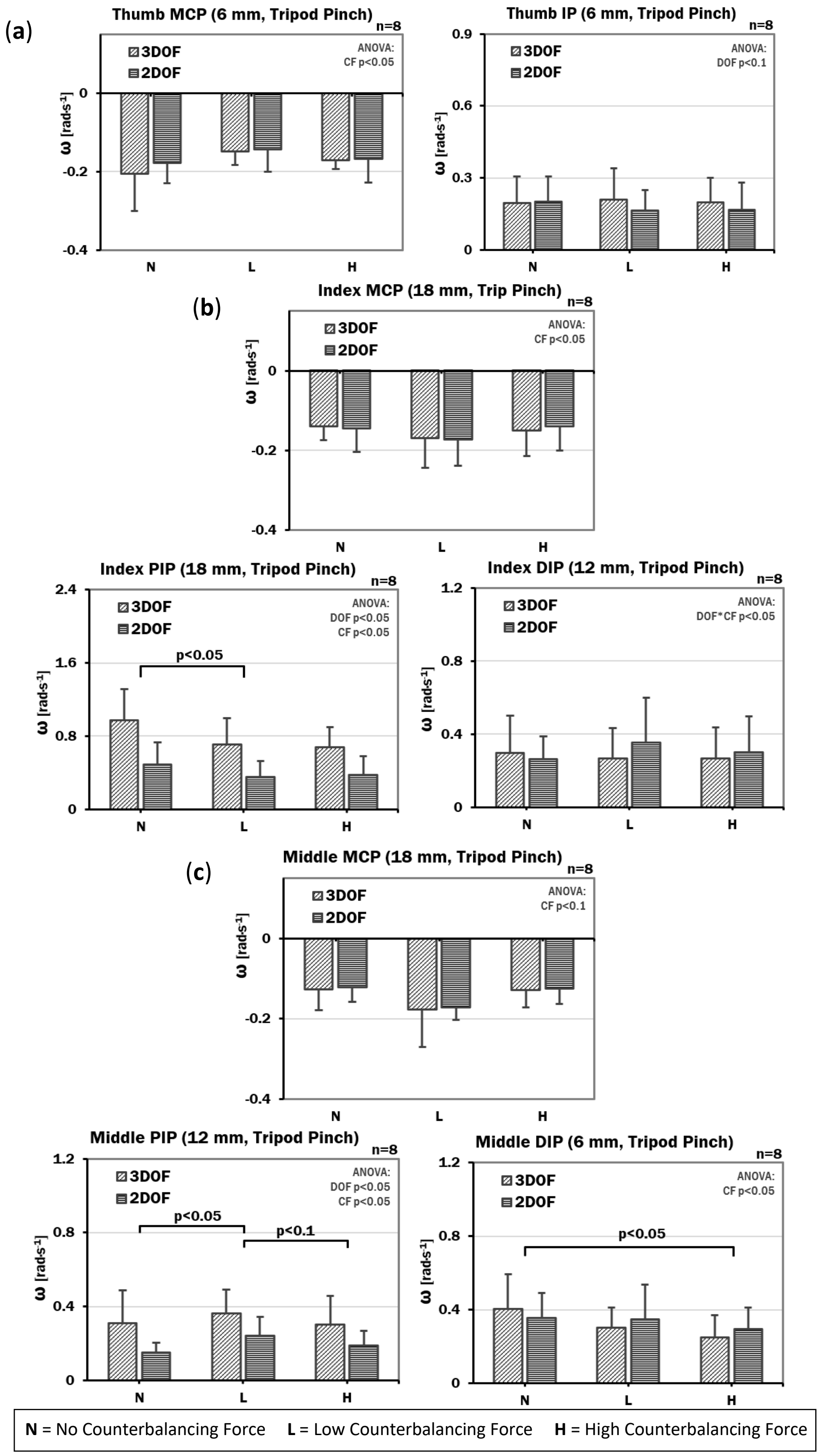


Figure 3.11 Counterbalancing force and DOF effect on the angular velocity at tripod pinch: **(a)** at the thumb; **(b)** at the index finger; **(c)** at the middle finger.

At the tripod pinch **(Figure 3.11)**, it is shown that the main effects were presented at all digits, but the interaction effect was only found at the index finger. For the thumb (**Figure 3.11.a**), a significant effect of counterbalancing force is indicated at the MCP joint. However, further exploration cannot indicate any AV difference among counterbalancing force conditions. Meanwhile, an effect of DOF was found on the IP joint in which 2 DOF brought a significant reduction in AV.

For the index finger (**Figure 3.11.b**), a significant effect of counterbalancing force was indicated on MCP and PIP joints. For the MCP, low counterbalancing force condition seemed to produce the highest AV but there was no difference indicated. Meanwhile, for the PIP, the difference was found between no counterbalancing force and low counterbalancing force. DOF also significantly affected the AV in this joint. On the other hand, there was an indication of the interaction effect at the DIP joint which showed the most noticeable AV increase in the 2 DOF setup with the low counterbalancing force exertion.

The middle finger result (**Figure 3.11.c**) presents the main effects on all joints. At the MCP joint, AV was significantly affected by the counterbalancing force. In this joint, even though the AV of low counterbalancing force condition looks the highest, there was no significant difference toward others. At the PIP joint, both significant effects of counterbalancing force and DOF were indicated. The AV of low counterbalancing exertion was significantly higher than others. The effect of the counterbalancing force was also significant at the middle DIP joint.

However, in this joint, a significant AV difference was shown between no counterbalancing force and high counterbalancing force.

3.3.3 Digit's Joints Angular Acceleration

From 39 separate analyses using ANOVA (**Table 3.5**), 18 significant main effects and six interaction effects were identified. Effects of DOF were mostly found on the index finger PIP joint at the tip pinch while at the tripod pinch, the effects were spread evenly on the index finger PIP, middle finger PIP, and middle finger DIP joint. On the other hand, the effects of counterbalancing force were dominant on the thumb MCP at the tip pinch and the middle finger PIP joint at the tripod pinch. Additionally, the interaction effects were distributed on the thumb and index finger for the tip pinch. However, at the tripod pinch, the interaction effects occurred on the index and middle finger.

Table 3.5. The $P(T \leq t)$ two-tailed value of two-way repeated measure ANOVA of AA affected by the DOF and counterbalancing force (CF); **(a)** at tip pinch; **(b)** at tripod pinch.

	(a) at tip pinch			**(b)** at tripod pinch		
	Insertion Depth			**Insertion Depth**		
	6 mm	**12 mm**	**18 mm**	**6 mm**	**12 mm**	**18 mm**
Thumb MCP						
DOF	0.934	0.606	0.366	0.763	0.764	0.975
CF	0.066 *	0.016 **	0.108	0.769	0.481	0.906
DOF×CF	0.798	0.215	0.844	0.837	0.641	0.198
Thumb IP						
DOF	0.788	0.376	0.921	0.161	0.648	0.330
CF	0.398	0.143	0.510	0.782	0.441	0.926
DOF×CF	0.028 **	0.459	0.475	0.668	0.670	0.530
Index MCP						
DOF	0.905	0.448	0.063 *	0.617	0.936	0.130
CF	0.187	0.158	0.151	0.132	0.038 **	0.144
DOF×CF	0.930	0.894	0.052 *	0.637	0.111	0.068 *

Index PIP						
DOF	0.016 **	0.001 **	0.009 **	0.079 *	0.168	0.005 **
CF	0.318	0.765	0.082 *	0.667	0.164	0.024 **
DOF×CF	0.617	0.077 *	0.898	0.514	0.502	0.599
Index DIP						
DOF	0.148	0.168	0.167	0.770	0.525	0.754
CF	0.217	0.559	0.152	0.540	0.636	0.346
DOF×CF	0.458	0.203	0.173	0.164	0.107	0.121
Middle MCP						
DOF				0.708	0.202	0.365
CF				0.996	0.326	0.254
DOF×CF				0.258	0.001 **	0.216
Middle PIP						
DOF				0.280	0.076 *	0.009 **
CF				0.066 *	0.020 **	0.076 *
DOF×CF				0.533	0.377	0.871
Middle DIP						
DOF				0.467	0.006 **	0.078 *
CF				0.368	0.667	0.934
DOF×CF				0.410	0.054 *	0.568

* $p < 0.1$ ** $p < 0.05$

At the tip pinch (**Figure 3.12**), significant main effects and interaction effects were found on the thumb and index finger. For the thumb (**Figure 3.12.a**), a significant counterbalancing effect was indicated on the MCP joint. In this case, the condition with no counterbalancing force brings the highest AA. Meanwhile, A significant interaction effect was found on the thumb IP joint. However, there was no indication of a difference in AA between conditions.

For the index finger (**Figure 3.12.b**), significant DOF effects, followed by significant interaction effects were indicated on the MCP and PIP joints. The effect of DOF at the PIP joint was stronger than the MCP in which 2 DOF setups brought lower AV. Meanwhile, the interaction effect on both joints was indicated by the higher the counterbalancing force exerted the less the AA difference (3 DOF vs 2

DOF) resulted. Furthermore, for the PIP joint, the condition without counterbalancing force showed a significant AA difference (3 DOF vs 2 DOF). For the DIP joint, 2 DOF setups seem to bring a reduction in AA and the reduction was increasingly visible as the application of the counterbalancing force is higher. However, there was no main or interaction effect found.

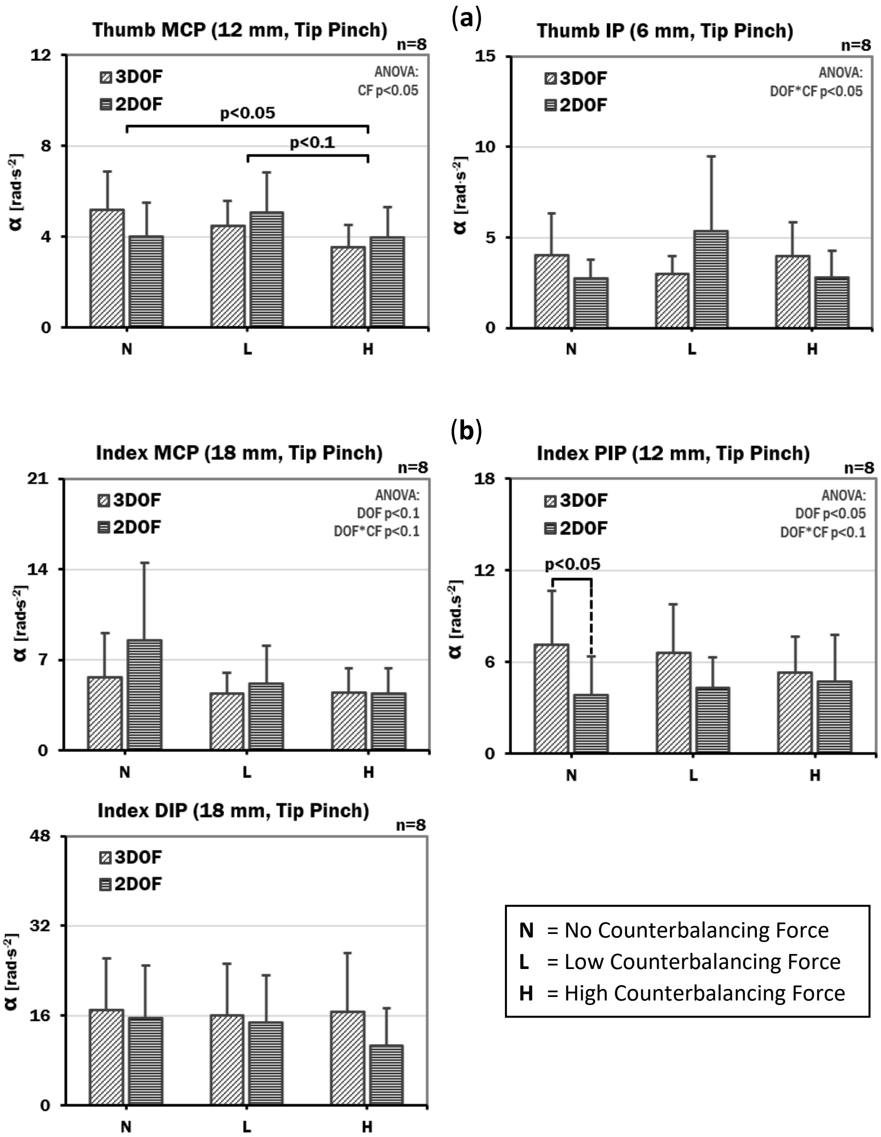


Figure 3.12 Counterbalancing force and DOF effect on the angular acceleration at tip pinch: **(a)** at the thumb; **(b)** at the index finger.

Based on the results at the tripod pinch (**Figure 3.13**), it is shown that the main effect and the interaction only occur on the index and middle finger. In **Figure 3.13.a**, no main or interaction effects were found at the thumb, nor were there any AA patterns leading to a certain trend. Meanwhile, at the index finger (**Figure 3.13.b**), counterbalancing force significantly affected AA of the MCP and PIP joint in which the condition without counterbalancing force exertion showed a slightly higher value. This was confirmed by the significant difference that was only found at the MCP joint, between low counterbalancing force and without counterbalancing force conditions. Especially for the PIP joint, the strong effect of DOF was also observed. This effect was indicated by lower AA at 2 DOF setup in each counterbalancing force condition. On the other hand, neither the main effect nor the interaction effect was found at the DIP joint.

For the middle finger (**Figure 3.13.c**), the main effects were indicated on PIP and DIP. At the PIP joint, AA due to low counterbalancing exertion was significantly higher than due to other conditions. Meanwhile, significant DOF effects were indicated on PIP and DIP joints. Opposite to the PIP, the AA of the DIP joint was higher at 2 DOF compared to the 3 DOF condition. Especially for the DIP joint, the DOF effect was followed by interaction in which the difference of AA at low counterbalancing force condition (3 DOF vs 2 DOF) was significant. The result at the MCP joint also presented an interaction effect. However, there was no significant difference among the conditions indicated.

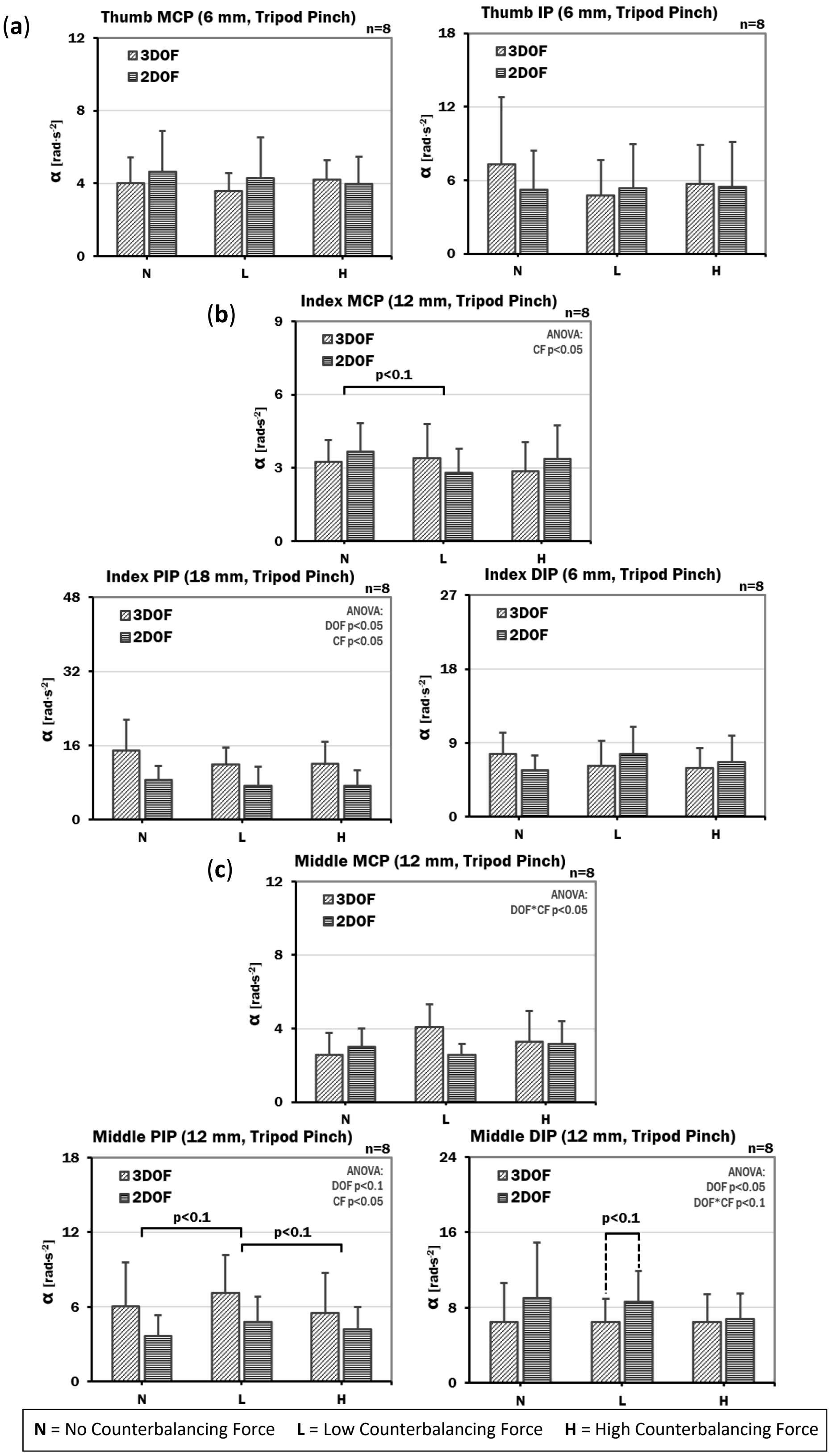


Figure 3.13 Counterbalancing force and DOF effect on the angular acceleration at tripod pinch: **(a)** at the thumb; **(b)** at the index finger; **(c)** at the middle finger.

3.3.4 Perceived Ease of Performing the Task

The results of the perceived ease of performing the task are presented in **Figure 3.14**. At the tip pinch, there was no significant effect indicated. The rating of conditions with counterbalancing force shows only a slightly better rating than without the force. Additionally, the DOF effect was also insignificant even though using 2 DOF setups was perceived as harder than 3 DOF. On the other hand, at the tripod pinch, the counterbalancing force did not bring a noticeable effect. However, the DOF effect was significant ($F(2, 7) = [20.25]$, $p = 0.003$) on the perceived ease of performing the task in which the conditions with 2 DOF setups show a lower rating than 3 DOF setups.

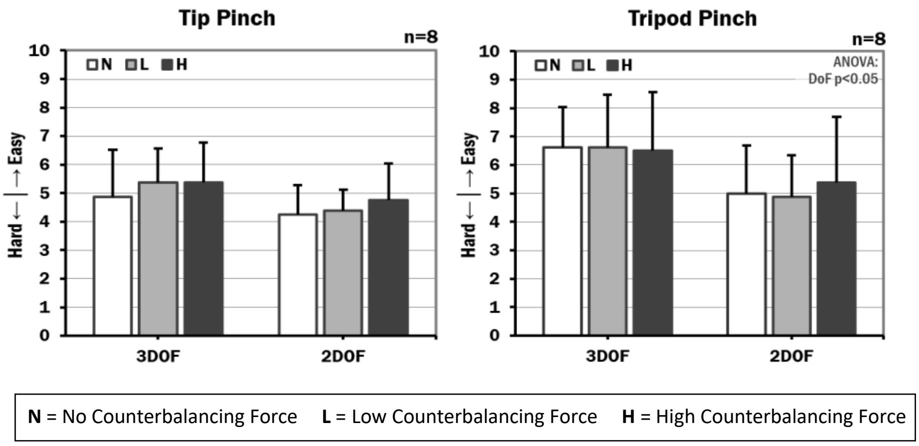


Figure 3.14 Counterbalancing force and DOF effect on the perceived ease of performing the task.

3.3.5 Insertion Time

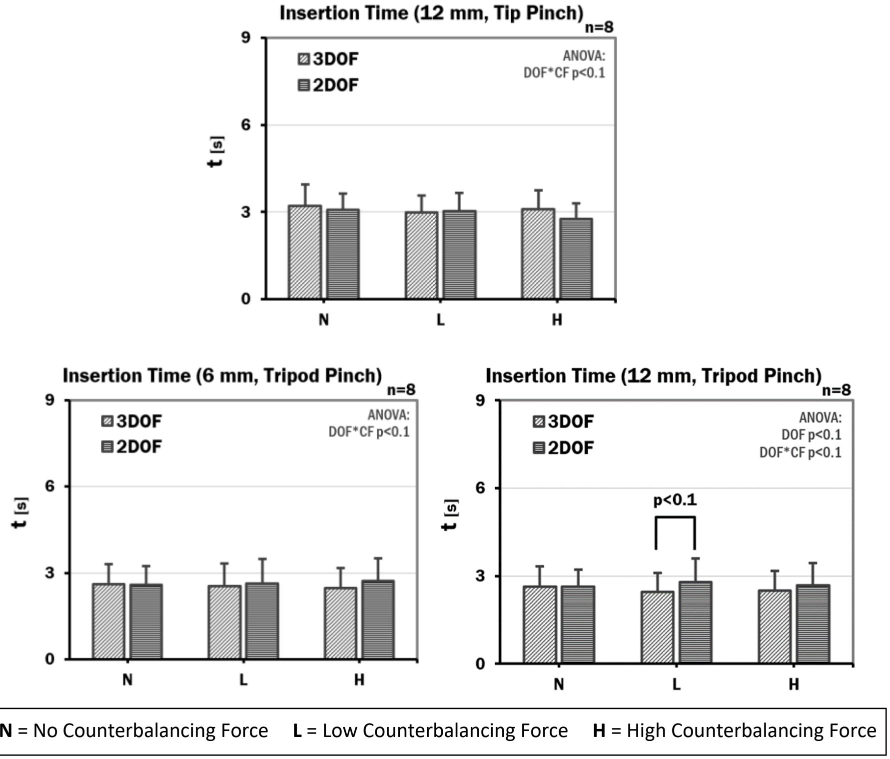


Figure 3.15 Effect of Counterbalancing Force and DOF on Peg Insertion Time

Insertions were performed in less than three seconds at the tripod pinch and more than three seconds at the tip pinch, in most conditions. From six analyses based on the type of pinch and insertion depth, only one significant main effect (effect of DOF) and three interaction effects were indicated. The insertion time is significantly affected by DOF ($p < 0.1$) only at tripod pinch when performing 12 mm insertion, in which a longer insertion time is presented for 2 DOF. However, a prominent time difference occurred at the tripod pinch only at a low counterbalancing force. After all, no differences were found in insertion time among different counterbalancing force conditions in every analysis in which interaction occurs.

3.4 Discussion

This study aims to investigate the effects of the counterbalancing force and DOF on the hand joint mobility function in performing fine hand use activities that were measured through the ROM, AV, and AA. The results of those parameters have been presented in the result section and need to be further discussed.

3.4.1 Peg Insertion Activity

In this study, the peg insertion activity was conducted using tip and tripod pinch. At the tip pinch, the index finger and thumb balance the grip of each other in which the index finger tends to have lower ROM than the thumb, as theoretically the longer and the more the link, the smaller the angle motion to produce a similar movement result (Holowenko, 1955). On the other hand, at the tripod pinch, the index fingers work side by side with the middle finger. Considering the Index and middle fingers have almost the same anatomy they will have almost similar ROM. Furthermore, based on Jo et al. (2019), at both pinch types, the thumb IP joint and fingers PIP joints will have the highest activity.

Hand joint mobility can be measured through movement range (ROM) and ease of movement (in this study is represented by AV and AA). Meanwhile, the size of the manipulated object affects the workspace of the digits' joints (Mackenzie & Iberall, 1994). Related to this, the insertion using a bigger peg size (tripod pinch) was performed with narrower joints ROM thus the insertion activity needs more wrist support. However, the AV and AA also represent the time aspect of the joint mobility in which their obtained results of the two parameters would not always be in line with their ROM (Fu, Gonzalez, & Lee, 1987; Winter, 2009).

Instructions for smooth movements cannot guarantee smooth movement results in peg insertion activities in this study. There were many irregular movements other than the ideal peg insertion movement pattern. When these irregular movements were processed into velocity and acceleration data, many fluctuations have been encountered. The appearance of these irregular movements was likely caused by adjustments that were intervened by the wrist joint and arm as the movements. This adjustment may make the peg movement smoother, but the movement of the digits' joints sometimes stops or even reverses.

In this study, the productivity aspect of the use of HE was analyzed through the time derivative of the joint angle parameters (AV and AA). However, participants were instructed to perform the task as smoothly as possible. Then, there will be a question: were there any effects of counterbalancing force and DOF on the insertion time? **Figure 3.15** shows that under the situation of smooth motion instructed, the effect of DOF and counterbalancing force on insertion time is not clear. It was most likely participants can control completion time without being affected by these two factors.

3.4.2 Effect of Counterbalancing Force

The existence of movement resistances that oppose the tendency of motion will reduce the ROM, AV, and AA. A counterbalancing force that works in line with the tendency of motion will work against the movement resistances and help to improve the parameters. Conversely, if the force is not in the direction of movement, joint mobility might be hampered. This force can be distributed due to the installation of an interdependent mechanism of the HE thus more parts of the hand will be helped. However, the direction of counterbalancing force is not always in line with the tendency of motion (such as in the insertion activity using 2 DOF setup on the PIP joint) making the counterbalance might not be effective or even hinder the mobility.

Clear evidence of ROM improvement due to the application of low counterbalancing force was indicated on the middle finger PIP joint (at tripod pinch) which is presented in **Figure 3.9.c**. This result was followed by an improvement in AV (**Figure 3.11.c**) and AA (**Figure 3.13.c**) confirming that the counterbalancing force improved the mobility of this joint. This is interesting because if the counterbalancing force is exerted on the proximal segment of each digit, then the effect should be high on the middle finger MCP joint, but the results do not show that. Allegedly this is due to the lower dynamic characteristics of the middle finger MCP joint compared to the PIP joint (Jo et al., 2019).

In situations when the counterbalancing force positively affected joint mobility, a low counterbalancing force (30 g) is confirmed more effective than a high counterbalancing force (100 g). The high counterbalancing force probably hinders reverse motion too much that causing the wrist to take over the movement. The wrist can be more active when there is difficulty in moving the digits (Montagnani, Controzzi & Cipriani, 2016; Liu et al., 2021). Meanwhile, the resistance of motion from the low counterbalancing force exertion did not provide sufficient stimulation to the wrist joint to interfere.

The parameters improvement that is exclusive to the middle finger shows that there was a slide in griping the peg during peg insertion. However, the participants were instructed to grip the peg without slide adjustment which can affect the motion measurement accuracy. Therefore, it is strongly suspected that the contact point of the middle finger to the peg was not at the fingertip but on the side of the distal phalanx between the tip and middle finger DIP joint, which is possible for tripod pinch (Feix et al., 2016). This peg-gripping method allows the motion of the middle finger more dynamic than the index finger without changing the peg motion during insertion.

Mobility of some joints tended to rise due to the non-significant effect of counterbalancing force which leads to the possibility of the force fine-tuning. For example, in **Figure 3.8.a**, there was an insignificant ROM improvement under low counterbalancing force application for the thumb MCP joint flexion at the tip pinch. This result was followed by its AV (**Figure 3.10.a**) and AA (**Figure 3.12.a**). The high incidence rate of insignificant improvement might also occur due to the small effect size (Montgomery, 2020). An in-line result was also shown in the perceived ease rating, especially at the tip pinch (**Figure 3.14**). In this result, the counterbalancing force exertion tends to raise the rating at both DOF setups, which means the participants felt a little helped by the force.

There were conditions in which counterbalancing force application potentially reduce joint mobility. On the index finger MCP joint at the tripod pinch (**Figure 3.9.b** and **Figure 3.13.b**), the exertion of the force showed lower movement parameters than in unexerted conditions. In situations such as in **Figure 3.9.b** or

Figure 3.12.b, too much counterbalance was confirmed to add resistance to the reverse motion that eventually causes joint mobility reduction. Mobility reduction on the MCP joint unsuccessfully triggered compensation by the PIP and DIP joints. This again shows the wrist joint's contribution in taking over the movement.

The peg insertion activity is a simultaneous movement of joints (MCP flexion – PIP extension – DIP/IP extension). In **Figure 3.11.b** and **Figure 3.11.c**, there were signs of AV improvement of MCP flexion due to low counterbalancing force exertion. However, these cannot bring a clear AV difference compared to the unexerted condition. Unfortunately, in **Figure 3.11.b**, the detrimental compensation emerged in the PIP joint extension since the PIP has bigger motion range characteristics. In **Figure 3.11.c**, since the low counterbalancing peg exertion successfully raises the AV (due to the more dynamic gripping method), the compensation goes to the DIP joint.

3.4.3 Effect of DOF

The Effect of DOF on ROM was similar to the results of Chapter 2. The DOF effect was dominant on the index finger PIP joint at the tip pinch (**Figure 3.8.b**) and the middle finger PIP joint at the tripod pinch (**Figure 3.9.b**). The situation is also the same for AV and AA. The logical explanation is the DOF affects all joints proportionally while the PIP joints have the highest ROM among other digit joints (Jo et al., 2019). Moreover, the predesigned motion of the 2 DOF linkage mechanism is inharmonious with the natural movement of peg insertion (flexed proximal phalanx and extended medial phalanx) and likewise when peg retraction.

The effect of DOF on the DIP joints is the opposite of the PIP joint (parameters at 2 DOF were higher than 3 DOF setups). This is quite reasonable because at 2 DOF the movement of MCP and PIP joints was restrained. In order to accomplish the insertion motion, other joints i.e., the DIP joints might take a more active role (Montagnani, Controzzi & Cipriani, 2016). Moreover, DIP joints were free from the linkage mechanism thus the motion resistance was minimum.

The result of the perceived ease rating (**Figure 3.14**), especially at tripod pinch, indicated a significant effect of DOF. The rating clearly shows that 3 DOF conditions are perceived easier than 2 DOF. At 3 DOF, a rating between 6 and 7 for all counterbalancing force conditions (almost similar for the three conditions) indicates that the task is easy to be performed thus the need to overcome that resistance is not yet apparent. Meanwhile, when 2 DOF is applied, the high counterbalancing force might give an advantage. However, a firm conclusion is still difficult to achieve since there is no interaction following the DOF effect.

3.4.4 Interaction Effect

Most of the interactions follow the significant DOF effect. In **Figure 3.8.b**, the ROM of index finger PIP joints at 2 DOF was lower than at 3 DOF. However, after applying the counterbalancing force, the ROM difference between the DOF setups became less significant. On this joint, the results of AV (**Figure 3.10.b**) and AA (**Figure 3.12.b**) were in line with the result of its ROM. Looking more closely at the results, the change was mostly on both DOF setups. This indicates a difference in the need for the counterbalancing force between the two setups which would be essential at 2 DOF but detrimental at 3 DOF setups. This is again understandable because of the one-direction work of the simple counterbalancing.

At the tip pinch, at the thumb IP joint (**Figure 3.8.a)**, the highest ROM difference between DOF setups is in low counterbalancing force conditions in which 2 DOF outperformed 3 DOF. This shows the detrimental effect of simple counterbalancing on a low-resistance setup. The result is in line with its AV and AA (**Figure 3.10.a** and **Figure 3.12.a**). Especially for the AA, the pattern was more prominent which emphasizes the role of the counterbalancing force at 2 DOF. On the other hand, at the tripod pinch (**Figure 3.9.c,** and **Figure 3.13.c**), the mobility parameters of the middle MCP joint rose only at 3 DOF. The possible cause is the high joint workspace of the 3 DOF setup that was supported by an appropriate counterbalancing force when performing the tripod pinch.

3.4.5 Design Direction

Simple and active counterbalancing showed the potential to improve hand joint mobility of the HE user. However, the counterbalancing force did not always effectively work against movement resistance in every joint. Especially when an interdependent linkage mechanism system is applied where there are joints that require movements that are not in rhythm with the predesigned movement of the interdependent system. Therefore, a strategy to optimize the role of the counterbalancing force is required.

The application of counterbalancing force for the MCP joints (low range of motion characteristics) was confirmed less effective, whether at 2 DOF or 3 DOF. Considering the motion resistance, the 3 DOF linkage mechanism is always recommended. On the other hand, looking at the interaction result (**Figure 3.8.b, Figure 3.10.b,** and **Figure 3.12.b)**, the counterbalancing force is expected to reach the PIP joint. A possible solution is changing the linkage system so that the actuator can directly drive the medial phalanx (a base-to-medial mechanism). Besides being more effective, this mechanism has an advantage in simplicity. The mechanism is also a more recommended alternative to a popular base-to-distal mechanism (du Plessis, Djouani, & Oosthuizen, 2021) which will make the links shorter (lighter and more stable) while clearing the distal tipping area.

Regarding how much a counterbalancing force should be exerted, it depends on the movement resistance which is difficult to measure thus a manual force adjuster is required to let the users set its level according to their preference. Additionally, because of its unique characteristics, counterbalancing activation requires a separate system that allows the use of sensors and actuators that are separated from the assistive force system. Although the counterbalancing force can be adjusted precisely, the resistance should be low from the beginning of HE wears because a high counterbalancing force will imply the reverse motion that eventually reduces the mobility of hand joints.

3.4.6 Limitations and Future Study

Similar to Chapter 2, this study still has limitations in participant number and type. The task variation and the counterbalancing force level are also limited. Future studies that explore the counterbalancing effect with more participants, variation of activities, and force levels are required. Furthermore, this study still considers peg insertion activity as a single manipulation movement. In further research, the separation of insertion and retraction movements can be carried out to study the effects of the counterbalancing force in each of these movements. On the other hand, this study suggests a base-to-medial linkage mechanism for a more effective counterbalancing application which effect of the counterbalancing force with this mechanism needs to be studied further.

3.5 Conclusion

The counterbalancing force has the potential to work against motion resistances produced by the HE mechanical system. Almost the results of AV and AA support the results of ROM. A small amount of an active counterbalance with a simple actuation can effectively make some joints that have a high motion range redeem their mobility that is previously constrained by the mechanical resistance of the HE. The magnitude of the force depends on how big the resistance is. Setups with a lower DOF require a higher counterbalancing force. Meanwhile, The counterbalancing force is less effective in setups with low movement resistance and may cause parameter decrement to other unexerted joints.

Chapter 4

General Discussion

A hand exoskeleton (HE) might provide a solution for improving hand function (Ferguson, Shen, & Rosen, 2020). Unlike assistive technology (AT) for other limbs, assistance purposed HE is still not widely used not only because the hand is a complex limb but also because the current design of HE does not consider the daily activities of the hand. Hand daily activities are dominated by fine hand use, carried out by precision grip (Vergara et al., 2014), in which hand joint mobility is important (WHO, 2001). However, most of the HE for assistance purposes are designed to alleviate power grips. Therefore, this thesis aims to study the human-machine interaction on a hand exoskeleton which is focused on the interaction between mechanical design characteristics of the HE and the joint mobility function of the user's hand in fine hand use activities. Two studies that have been conducted in this thesis are summarized in the following section.

4.1 Summary

The first study of this thesis aimed to investigate the effects of the weight and DOF of the HE on the hand joint mobility function while performing fine hand use activities. This study results in some important findings. First, wearing an HE will generally reduce hand joint mobility due to the movement resistance from its mechanical system. Second, the weight added to the digits may improve the movement range aspect of hand joint mobility. Third, managing the digit's weight becomes more important in the low DOF mechanism. Based on the findings, a study regarding the counterbalancing force that might be a potential solution to counter the movement resistance was proposed.

The second study of this thesis aims to investigate the effects of the counterbalancing force of the hand exoskeleton on hand joint mobility function. This study includes the investigation of DOF reduction in the application of the counterbalancing force. Some important findings have resulted from this study. First, the counterbalancing force has the potential effect to work against motion resistances produced by the HE mechanical system. Second, the counterbalancing force improved hand mobility on joints that have a high movement range. Third, the application of counterbalancing force on joints with lower movement resistance and lower movement range is less effective. A detrimental effect on other digit joints may occur as compensation for this insignificant movement parameter improvement. From these findings, some design directions for the HE can be proposed. First, a base-to-medial linkage mechanism is recommended to achieve more effective counterbalancing while getting lower movement resistance. Second, a manual adjuster is essential for letting the users set the force according to their preferences. Third, to activate the counterbalancing force, different sensors from the sensors of the assistive force are recommended thus the form factor and attachment technique of the sensor are crucial in reducing wearing complexity. Of course, it would be better if the counterbalancing force can be effective in two directions.

4.2 Implications

Combining the results of the first and the second study, the use of HE has a detrimental impact on the mobility of hand joints when performing fine hand use activities because of the presence of mechanical resistances. This disadvantage can be seen both from the aspect of ease of movement and movement range. Meanwhile, efforts to reduce the number of actuators through DOF reduction actually add to the resistances drastically, which is dominated by a discrepancy between the predesigned motion of the linkage mechanism and the required movement of manipulating objects. Although the hands were able to complete all experiment tasks in both studies due to the contribution of the wrist joint, arm, and compensatory movements of some digit joints, it was clear that difficulties due to DOF reduction were experienced by the participants. This leads to one view that reducing DOF in HE to reduce design complexity in general, should be avoided.

Based on the results of the first and the second study, although built with the same logic: providing a force that works against movement resistance, active counterbalancing forces brought different impacts from the finger loads. The loads that were distributed over all digits' segments totally fit with the insertion activity. On the other hand, even though active counterbalancing has the advantage of not adding weight to the digits (which was proven to reduce productivity in the first study), it was utilizing the linkage mechanism to reach more digit segments which ultimately brings resistance to movement. Results of the second study show that application of the mechanism turned out to bring more losses than gains. Moreover, the joints that are effectively helped by both treatments are also different, where the application of finger loads was able to suppress ROM reduction on MCP and DIP joints at the tip pinch. Meanwhile, the positive counterbalancing effects were more dominant in the mobility of the middle PIP joints at the tripod pinch. From the second study, it can be known that the middle finger was more dynamic than other digits during insertion. These different results can have ramifications for future HE designs. Systems that adopt DOF reduction require a resistance handling of many segments or at least implementing a careful segment weight setting. Whereas HE with high flexibility accommodation, e.g. without DOF reduction, can focus on transmitting the counterbalancing force directly to the most active segment, namely the medial. However, anyway, the adoption of any system that can reduce the DOF should be avoided.

Merging the solutions and design directions from the two studies might answer questions of how to make an HE design that can provide assistive force to alleviate muscle work while maintaining hand skills in fine hand use activities. In other words, the question is how to make a system that is concise but effectively functional in these two different situations. By focusing the discussion on an HE system without DOF reduction and with a base-to-medial concept, a more detailed question: is two separate control systems and actuators still required to provide both functions? The answer is yes because the required characteristics of the control system of those two functions are completely different. Unfortunately, doing this would make the HE becomes bulky and complex unless there is a technological leap in the actuator form factor. An alternative solution for this problem is to place large, powerful actuators away from the hand connected to long transmission (i.e. a Bowden cable) while small and fast actuators can be placed on the carpals to generate the counterbalancing force. As a note, this method will increase the number of components and reduce the wearability and portability of the entire system.

4.3 Limitations and Future Research

Based on the efforts that have been made, this research is still constrained by several limitations. The HE prototypes preparation was very complex caused studies in this thesis to have an obvious limitation in the number and type of participants (due to difficulties to provide one prototype per participant). The factors' levels were still also limited due to the design complexity of the HE prototypes and the technical complexity to run the experiment. Additionally, the task is limited to the pegboard tests which each measure only the tip and tripod pinch. On the other hand, the prototype itself still has weaknesses, for example in the attachment system with double-sided tape, which is inconvenient, but so far there has been no other, more reliable option. Especially the active HE types, still have some limitations, for example, the actuator speed of 25 mm/s is not sufficient to be used in a dexterity test.

Future research involving more participants (number and type) is required. Exploration of hand movements both in terms of depth of analysis and variety of activities is also essential. For those purposes, some specifications of the prototype and testing equipment also need to be improved, especially on the actuator speed. Meanwhile, studies of a more effective linkage mechanism for providing counterbalancing force as it is recommended in Chapter 3 are also important to conduct. It will be interesting to compare the user interaction with the base-to-proximal and the base-to-medial HE system. On the other hand, applying both the counterbalancing force and the assistive force requires a unique mechanical, control, and sensing system that can be the next challenge in the HE technological research area. Furthermore, extended research in the area of concept development to seek a new strategy to maintain the design complexity of a daily use HE is also interesting to conduct.

4.4 General Conclusion

This research has shown that the mechanical characteristics of the HE, especially DOF, and the weight of the digits are important factors to consider in designing an assistive HE for daily use. Reducing the DOF of the HE will reduce the user's hand joint mobility while adding weight to the digits of the HE in a certain condition will counterbalance movement resistance and improve movement range. On the other hand, similar to weight addition, active counterbalancing has shown its potential in improving hand joint mobility. However, a strategy to apply the counterbalancing force is required because it works effectively on the PIP joints but is detrimental to the MCP joints. These results might bring implications to future HE designs. A base-to-medial design is a recommended strategy to directly deliver the counterbalancing force to the medial segment without reducing DOF and maintaining low design complexity. Additionally, separation of the HE controls system is required to provide functionality in both fine hand use performance and muscle strength assistance.

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